DEVELOPMENT OF GEOPOLYMER CONCRETE INCORPORATING LOCAL WASTE MATERIALS

BY

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بسم الله الرحمن الرحيم

This work is dedicated to my dear parents, wife,

brothers, sisters and daughter.

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ABSTRACT

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The concrete industry is one of the largest producers of carbon dioxide (CO_2) emissions in the world. The produced carbon dioxide (CO_2) emissions is directly proportional to the Portland cement production, which is the primary ingredient of concrete. Therefore, there is a concentrated effort to decrease the greenhouse gas emissions by the use of alternative cementing materials such as geopolymers.

Current study investigated the utilization of geopolymer concrete to minimize the use of Portland cement. Geopolymer concrete is considered as a green material that can be produced using materials other than Portland cement. Fly ash and ground granulated blast furnace slag are the mostly used materials in producing geopolymer concrete. However, these materials are not available locally in Saudi Arabia. Therefore, there is a need to develop geopolymer concrete utilizing local materials.

In this study, the available local materials activated by two different alkaline solutions were considered as binding materials in producing geopolymer concrete. Locally available Natural pozzolan, kaolin, and limestone powder were used to develop geopolymer concrete. Different ratios of Na_2SiO_3/NaOH and Na_2SiO_3/KOH were used to prepare geopolymer concrete. A total of 54 of geopolymer concrete mixtures were prepared, heat-cured for 7 days and tested for compressive strength. Based on the results of the preliminary

investigation, a total of 8 mixtures were selected for detailed study evaluation to assess their mechanical properties, acid resistance, thermal resistance, shrinkage, and durability characteristics.

Among the three cementitious materials considered, natural pozzolan was found to be the best performing. The use of kaolin and limestone powder for producing geopolymer concrete is not recommended because of their poor performance. Two Natural pozzolan-based mixtures: (i) with 85% NP, 15% Portland cement by mass activated using NaOH using a Na_2SiO_3/NaOH ratio of 4.0 and (ii) with 85% NP, 15% Portland cement by mass activated using KOH using a Na_2SiO_3/KOH ratio of 4.0, are recommended for producing structural geopolymer concrete.

MASTER OF SCIENCE DEGREE
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ملخص الرسالة

الاسم الكامل: عباس بن احمد بن ابراهيم البوشقراء

عنوان الرسالة: تطوير الخرسانة المنشطة بالمحاليل القلوية بالاستفادة من المواد المحلية

التخصص: الهندسة المدنية (إنشاءات)

تاريخ الدرجة العلمية: يونيو 2016 م

صناعة الخرسانة تعتبر من أكبر منتجي انبعاثات غاز ثاني أكسيد الكربون في العالم. كما أن كميات غاز ثاني أكسيد الكربون المنبعثة متناسبة طرديا مع الكميات المنتجة من الأسمنت البورتلاندي، وهو العنصر الأساسي في صناعة الخرسانة. لذلك، اللحفاظ على انبعاثات غاز ثاني أكسيد الكربون في مستويات منخفضة يتطلب استخدام خرسانة بديلة كالخرسانة المنشطة بالمحاليل القلوية.

الدراسات الحالية قد حققت الاستفادة من عدة مواد في إنتاج خرسانة بديلة، وذلك للحد من استخدام الاسمنت البورتلاندي. تعتبر الخرسانة المنشطة بالمحاليل القلوية؛ خرسانة خضراء ،ويمكن أن تنتج باستخدام مواد أخرى غير الاسمنت البورتلاندي من قبل تنشيطها باستخدام محلول قلوي. الرماد المتطاير ومسحوق خبث الفرن العالي هي مواد تستخدم في الغالب في إنتاج هذا النوع من الخرسانة. ولكن، هذه المواد لا تتوفر محليا في المملكة العربية السعودية. لذلك، فإننا نحتاج الى مزيد من الدراسات في إمكانية الاستفادة من المواد المحلية في هذا النوع من الخرسانة.

في هذه الدراسة، تم استخدام المواد المحلية المتاحة، وتم تنشيطها من قبل اثنين من المحاليل القلوية المختلفة في إنتاج مخاليط من الخرسانة. فقد تم استخدام البوزولان الطبيعي، والكاولين، ومسحوق الحجر الجيري لانتاج الخرسانة المنشطة بالمحاليل القلوية. نسب مختلفة من سيليكات الصوديوم /هيدروكسيد الصوديوم و سيليكات الصوديوم /هيدروكسيد البوتاسيوم تمت تجربتها في انتاج الخرسانة المنشطة بالمحاليل القلوية. فقد تم إنشاء مجموعه من أربعة وخمسين خلطة مختلفة من الخرسانة المنشطة ،ومعالجتها بالحرارة لمدة سبعة أيام ،وثم اختبارها لقوة الضغط ضمن الدراسة الأولية. وبناء على نتائج الدراسة الأولية، فقد تم اختيار مجموعه متكونة من ثمان خلطات للدراسة المفصلة، والتي تتكون من :تقييم خواصها الميكانيكية، ومقاومتها للاحماض ، ومقاومتها للحرارة العالية، وانكماشها، وديموميتها.

نتائج التقييم المفصل للخلطات الثمانية المنتقاة تشير إلى أن من بين الثلاث المواد المحلية المستخدمة؛ فإن أداء البوزولان الطبيعي كان الأفضل. فلا ينصح باستخدام الكاولين ومسحوق الحجر الجيري لإنتاج الخرسانة المنشطة بسبب أدائها الضعيف. كما أن اثنتين من الخلطات المنشطة تم ترشيحها من قبل هذه الدراسة للتطبيق كخلطات خرسانية إنشائية. الخلطة الأولى تحتوي على 85% من البوزلان الطبيعي و 15% من الاسمنت البورتلاندي، ومنشطة باستخدام نسبة مساوية الى 4.0 من سيليكات الصوديوم / هيدوكسيد الصوديم. والخلطة الثانية تحتوي على 85% من البوزلان الطبيعي و 15% من الاسمنت البورتلاندي، و منشطة باستخدام نسبة مساوية الى 4.0 من سيليكات الصوديوم / هيدوكسيد البوتاسيوم.

درجة الماجستير في الهندسة المدنية

جامعة الملك فهد للبترول والمعادن

الظهران 31261

المملكة العربية السعودية

CHAPTER 1

INTRODUCTION

1.1 General

The global concrete consumption happens to be second only to water. However, the common primary binder in producing traditional concrete is the ordinary Portland cement (OPC) material [1,2], which manufacturing process generates large quantities of carbon dioxide (CO_2) emissions posing a severe risk of air pollution. It is reported that producing one ton of OPC results into generation of nearly a ton of CO_2 emissions in the open atmosphere. Since, nowadays, the world is moving towards the concept of a safe environment with low greenhouse gas emissions, and low waste production, there is growing concern to reduce the consumption of Portland cement for reducing the CO_2 emissions [2,3].

As such, there is a growing interest in utilizing waste materials including different classes and grades of fly ash, and ground granulated blast furnace slag in making geopolymer concrete [4].

The term 'Geopolymer Concrete' was introduced in 1978. It was described that geopolymer concrete is unlike OPC concrete because the calcium silicate hydrate (C-S-H) matrix is not formed. Rather, the structural strength in geopolymer concrete is attained by the formation of polymer condensation of by alumina and silica [4]. Thus, geopolymer

concrete binding materials is preferred to have high contents of silica and alumina. Examples of such materials are fly ash, granulated blast furnace slag and natural pozzolan. On the other hand, limestone powder and cement kiln dust are rich in lime and alkalis, but not in silica and alumina contents. So, the shortage of silica and alumina contents in limestone powder and cement kiln dust can be compensated either by adding a sodium silicate source material.

The addition of sodium silicate solution to the mixture made the reaction occur at higher rates and improved the resulted binding product when compared to the use of alkali only [5]. The performance of alkali-activated binders depends on the concentration of alkali used for activation of the binders as well. Generally, geopolymer concrete activated with higher sodium hydroxide concentrations gives higher compressive strength [6].

This research work investigated the use of the available local materials in making geopolymer concrete. Natural pozzolan, kaolin, and limestone powder activated by two types of alkaline materials, sodium hydroxide (NaOH) and potassium hydroxide (KOH), were used in preparing the geopolymer concrete mixtures. Sodium silicate (Na_2SiO_3) was used as a source of silica in the binders. The variables in producing different trial mixtures of geopolymer concrete included types of natural/waste materials, NaOH/ Na_2SiO_3 ratio, KOH/ Na_2SiO_3 ratio, replacements of OPC at different percentages including the case of full replacement. Several trial mixtures of geopolymer concrete were prepared and tested for compressive strength. From each group of the geopolymer concrete mixture, the mixture (s) having acceptable compressive strength were selected for detailed testing and evaluation. Finally, based on the evaluation of performance, conclusions and

recommendations were drawn, which might be useful in producing geopolymer concrete mixtures utilizing local materials in Saudi Arabia.

1.2 Need for this Research

Several types of local materials including natural pozzolan, kaolin, and limestone powder can be utilized in producing geopolymer concrete. However, the required information is lacking. Thus, there is a need for conducting studies to identify the potential of those local binding materials in making geopolymer concrete. In addition, the use of the local geopolymer binders would reduce the consumption of OPC in manufacturing concrete and that would help in reducing the greenhouse gas emissions to the open atmosphere.

1.3 Research Objectives

The main objective of this proposed work was to explore the possibility of developing geopolymer concrete mixtures using the local materials.

The specific objectives of this research were as follows:

1. Develop different geopolymer concrete binders from the local available materials including natural pozzolan, kaolin and limestone powder were activated using different alkaline solutions, i.e. NaOH, and KOH,
2. Evaluate the performance of the optimum (selected) geopolymer concrete mixtures in terms of their mechanical properties, acid resistance, thermal resistance and durability characteristics.

1.4 Research Blueprint

The research work was accomplished in four phases, as follows:

- **Phase no. I:**

  The first phase involved acquiring a comprehensive background of geopolymer concrete through the literature review.

- **Phase no. II:**

  The second phase involved preparing total of 54 different trial mixtures of geopolymer concrete considering the key variables, as mentioned earlier. Based on the strength of the trial mixtures, eight geopolymer concrete mixtures were selected for the detailed study.

  Phase III:

  The third phase involved evaluation of the performance of the selected geopolymer concrete mixtures in terms of their mechanical properties, acid resistance, thermal resistance and durability characteristics.

  Phase IV:

  The last phase involved conclusions and recommendations based on the evaluation of performance of the developed geopolymer concrete mixtures.

CHAPTER 2

LITERATURE REVIEW

2.1 Background of Geopolymer Concrete

Geopolymerization is a chemical reaction that incorporates minerals in the presence of silico-aluminates. Any source of silica and alumina that easily dissolve in an alkaline solution is a precursor for geopolymerization. The alkali activator is any compound from the first element in the periodic table, e.g. sodium and potassium. Therefore, such materials are also called alkali-activated silico-aluminates or alkali activated cementitious materials. The resulting inorganic geopolymer product from the geopolymerization reaction is an amorphous equivalent to the geological feldspar. Also, the alkali-activated materials are also called "geopolymers" [7].

The hardening mechanism in the geopolymerization chemistry involves the dissolution of silica and alumina in the presence of an alkaline solution. Then, alkalization and formation of bonds between aluminum and silica by sharing oxygen atoms make tetrahedral interlinked structure. Basically, attachment of the hydroxide base to the Al-O-Si bond forms the building block of the geopolymeric structure [7].

Moreover, the geopolymers differ from the pozzolanaic cements since the geopolymerization utilizes the poly-condensation of silico-aluminates to form the structural strength through the polymeric silicon-oxygen-aluminum (Si-O-Al) bonds. On the other hand, the hydration of pozzolanaic cements form the calcium-silicates hydrate (C-S-H) which is the pathway to attain the structural integrity of the OPC type of concrete

[7]. The common alkaline liquid used in the geopolymerization reaction is the combination of Sodium hydroxide/ Potassium hydroxide and Sodium silicate/ Potassium silicate [8].

2.2 Evaluation of the Flow Properties of Geopolymer Concrete

The recent studies, which investigated the flow of the geopolymer concrete, stated that the variation of ambient temperature, moisture content of aggregates, mixing time, and degree of condensation reaction were considered as essential factors affecting the slump value [9]. Moreover, the molarity of the alkaline solution could enhance the workability of geopolymer concrete mixture. It was reported that the workability of geopolymer concrete was reduced with higher concentrations of sodium hydroxide [10]. Also, water to geopolymer ratio could not be increased beyond certain limit since workability could not be enhanced at a cost of compressive strength [11]. But, to improve the workability of fresh geopolymer concrete, a high-range water-reducing admixture can be incorporated 60 seconds before the end of the mixing cycle [12].

2.3 Evaluation of the Hardened Properties of Geopolymer Concrete

The literature review presented below pertains to the evaluation of the performance of hardened properties of the geopolymer concrete mixtures made utilizing fly ash, ground granulated blast furnace slag GGBS, natural pozzolan, kaolin and limestone powder. Various hardened properties were considered including compressive strength, splitting tensile strength, modulus of elasticity, water absorption, thermal resistance, acid resistance and drying shrinkage characteristics.

2.3.1 Compressive Strength

Many studies had investigated the compressive strength development of geopolymer concrete. It was observed that the compressive strength increased when the molarity of sodium hydroxide was increased. On the other hand, a decrease in the compressive strength was observed when the amount of alkaline liquid to alumina-silicate source material i.e. fly ash ratio was increased [13]. Geopolymer concrete with lower liquid / binder ratio developed higher compressive strength than companion mixtures with higher liquid / binder ratio due to increasing friction between particles at lower liquid / binder ratio [14]. Furthermore, it was found that water curing and room temperature curing were not effective in case of geopolymer concrete. In addition, a minimum curing period of 24 hours using steam curing or hot air curing is sufficient to harden the geopolymer concrete [15].

The strength development of low calcium fly ash based geopolymer concrete, activated by a combination of sodium silicate and sodium hydroxide and subjected to initial heat curing at 60 °C for 24 hours, was studied by Ramujee and Potharaju [16]. They found that the 3 days' compressive strength of the initial heat-cured specimens was more than 40 MPa whereas less than 10 MPa was reported for the ambient cured specimens for the same curing period. This indicates the beneficial effect of the initial heat curing on evolution of the strength of geopolymer concrete.

Moon et al. [17] studied the strength development of geopolymer concrete made using natural pozzolan and heat-cured at 80 °C. Their study considered two mixtures; first was activated by sodium hydroxide solution alone and the second was activated by using sodium silicate to sodium hydroxide ratio of 0.25. Results showed that the 28-day compressive strength of the first mixture was 33 MPa whereas more than 45 MPa was

reported for the second mixture. This indicates the positive effect of using sodium silicate besides sodium hydroxide in activating natural pozzolan material.

Heah et al. [18] studied the strength development of kaolin based geopolymer concrete mixture which was heat-cured at 100 °C for 2 days prior to air dry curing. It was activated using a sodium silicate to sodium hydroxide ratio of 0.32. However, the 28-day compressive strength was lower by 25% compared to its 7-day compressive strength. The resulted loss of strength was probably because of early heat curing at a high temperature i.e. 100 °C for a duration of 2 days [18].

Furthermore, Cwirzen et al. [19] conducted experimental works to investigate the strength development of 20 °C heat-cured geopolymer concrete mixture for 24 hours. The studied mixture's binding material consisted of 70% limestone powder and 30% metakaolin. It was activated by sodium hydroxide of 5 Molar at water to binder ratio of 0.7. Then, they were either wet-cured or air-dried at room temperature until the day of testing. Results showed that the compressive strength after 28 days of curing for the wet-cured specimens was approximately 2.5 MPa whereas around 4 MPa was reported for the dry cured specimens at the same curing period. It was believed that the obtained low compressive strength was probably because of use of the sodium hydroxide solution alone to activate the mixture. However, it was suggested that replacing sodium hydroxide by sodium silicate in the mixture would result to higher compressive strength [19].

2.3.2 Splitting Tensile Strength

Yellaiah et al. [20] investigated the strength development of fly ash based geopolymer mortar that was activated by a ratio of sodium silicate to sodium hydroxide of 2.0. The

activator to fly ash ratios were 0.3, 0.35 and 0.4. Specimens were left at a maximum heating temperature of 60 °C for 24 hours. Then, they were air-dried in the laboratory until the day of testing. The obtained results showed that the splitting tensile strength increased with increasing the activator to binder ratio [20].

Splitting tensile strength of natural pozzolan based geopolymer concrete mixtures reported higher results than OPC mixtures at longer ages [21]. The investigated mixtures were activated by a ratio of potassium hydroxide to sodium silicate of 7.70. The optimum temperature of curing was found to be 40 °C. The reported results showed that a higher water to binder ratio resulted in lower tensile strength [21].

2.3.3 Modulus of Elasticity

Madheswaran et al. [6] investigated the modulus of elasticity of ambient-cured fly ash - slag geopolymer concrete mixtures. It was reported that the modulus of elasticity was in the range of 13.5 to 14.1 GP when ambient curing was carried. However, the tested specimens were activated by a combination of sodium hydroxide and sodium silicate solution.

Diaz-Loya et al. [12] studied the elastic modulus of fly ash geopolymer concrete mixtures activated by a combination of sodium hydroxide and sodium silicate solution and heat-cured at 60 °C for 3 days. The geopolymer concrete mixtures achieved the elastic modulus of up to 43 GPa [12]. Xie and Ozbakkaloglu [14] found that the modulus of elasticity of geopolymer concrete increases with an increase in the compressive strength for mixtures activated by an alkaline combination of sodium silicate and sodium hydroxide solution .

2.3.4 Water Absorption

The water absorption of room temperature cured kaolin based geopolymer concrete was reported to vary in the range of 8% to 27% [22]. The curing using elevated temperature affected the absorption of geopolymer concrete. For example, when curing temperature was increased from room temperature to 500 °C for Enugu kaolin based geopolymer concrete mixtures, the water absorption decreased from 27% to 13% [22].

Thokchom et al. [23] noted a reduction in the water absorption of heat-cured low calcium fly ash based geopolymer mixtures when a higher percentage of sodium oxide (Na_2O) was used for activation. It was reported that the water absorption of geopolymer mortar showed 50% decrease when the percentage of sodium oxide was increased from 5% to 8% [23].

2.3.5 Acid Resistance

The acid resistance of fly ash and ground granulated blast furnace slag (GGBS) based geopolymer concrete mixtures was studied by Kumaravel et al. [24]. It was reported that the reduction in compressive strength in the range of 1.4 % to 7.25 % when exposed to hydrochloric acid (5% concentration) for 90 days. In the similar situation, the reduction in compressive strength for OPC concrete was reported to be in a range of 4.9 % to 10.2 % [24]. Gopal and Kiran [25] reported the loss of compressive strength of OPC concrete was two times the loss of geopolymer concrete after sulfuric acid exposure at all ages.

2.3.6 Thermal Resistance

Hossain et al. [26] reported an initial increase in compressive strength of cement fly ash geopolymer mortar mixtures when exposed to temperature up to 200 °C. The thermal resistance of heat-cured geopolymer concrete mixture containing a binding material of

phosphogypsum, fly ash and cement kiln dust was studied by Khater and Sayieda [27]. It was found that firing treatment for both 10 % and 20 % phosphogypsum mixes had a lower strength values up to 800 °C, while strength exposed to strength gain up to 1200 °C.

2.3.7 Drying Shrinkage

The drying shrinkage of room temperature cured geopolymer concrete was found to be comparable to normal OPC concrete of similar compressive strength up to the age of 180 days [28]. It is believed that most of the released water during the chemical reaction may evaporate when using heat-curing process leaving behind a small quantity of micro-pores water in the hardened concrete [29]. Castel et al. [30] believed that the drying shrinkage of is reduced because of the reduction in the average pore size of geopolymer concrete during heat treatment.

A study on the drying shrinkage of an alkali-activated blended slag with low calcium fly ash geopolymer concrete mixture, reported by Castel et al. [30], indicated that the geopolymer concrete mixtures perform well with regard to the drying shrinkage when the duration of curing is long irrespective of the curing temperature. However, it was concluded that the geopolymer concrete heat-treated at 80 °C for a minimum of one day would result to a final drying shrinkage less or similar to that in OPC concrete [30].

CHAPTER 3

Methodology of Research

3.1 Introduction

In this chapter, first, the sources and characteristics of the materials used to prepare geopolymer concrete mixtures, such as cementitious materials including cement, natural pozzolan, kaolin, and limestone powder in addition to the activating agents, aggregates and superplasticizer are described. Secondly, the details of experimental work including the key mixture variables considered to design and produce 54 trial mixtures of geopolymer concrete are explained. Finally, the curing, aggressive exposure conditions and test methods used to evaluate the performance of the geopolymer concrete mixtures are detailed.

3.2 Materials used in Geopolymer Concrete Mixtures

The materials used to prepare the mixtures of geopolymer concrete included cementitious materials (cement, natural pozzolan, kaolin, and limestone powder), alkaline chemicals used for activation (sodium hydroxide, potassium hydroxide and sodium silicate), fine aggregates, coarse aggregates, and superplasticizer.

3.2.1 Cementitious Materials

(i) Ordinary *Portland Cement (OPC)*

The used ordinary Portland cement (OPC) in this research was Type I according to ASTM C 150 (Figure 3-1). It was obtained from a cement plant located in Al-Ahsa in the eastern

region of Saudi Arabia. This type of cement is known as the "*General Purpose Cement*" and it is commonly used in the construction works in Saudi Arabia unless other type of cement is stated. Its specific gravity is 3.15. Table 3-1 shows the chemical composition of the used OPC in this study.

Figure 3-1: Ordinary Portland Cement (OPC) Type I

Table 3-1: Chemical Composition of the Ordinary Portland Cement (OPC) Type I

Component	Weight %
CaO	64.35
SiO_2	22.00
Al_2O_3	5.64
Fe_2O_3	3.80
K_2O	0.36
MgO	2.11
Na_2O	0.19
Equivalent alkalis	0.33
SO_3	2.10
Loss on ignition	0.70
C_3S	55.00
C_2S	19.00
C_3A	10.00
C_4AF	7.00

(ii) Natural pozzolan (NP)

The siliceous natural pozzolan used in this research was obtained from the western region of Saudi Arabia. It was acquired from the volcanic rocks and had a dark gray color (Figure 3-2). Its specific gravity is 3.00. Table 3-2 shows the chemical composition of the used natural pozzolan.

Figure 3-2: Local Natural pozzolan Material

Table 3-2: Chemical Composition of the Used Natural pozzolan Material

Component	Weight %
CaO	8.06
SiO_2	42.13
Al_2O_3	15.33
Fe_2O_3	12.21
K_2O	0.84
MgO	8.50
Na_2O	2.99
$Na_2O + 0.658\ K_2O$	3.54
Moisture	0.17

(iii) Kaolin

The kaolin used in this study was obtained from Al-Ahsa in the eastern province of Saudi Arabia. The specific gravity of the obtained kaolin was 2.73 with light brown color (Figure 3-3). Table 3-3 shows the chemical composition of the kaolin used in this research.

Figure 3-3: Local Kaolin Material

Table 3-3: Chemical Composition of the Used Raw Kaolin Material

Element	Weight %
C	18.04
O	42.85
Na	0.83
Mg	1.57
Al	6.26
Si	17.90
Cl	0.67
K	1.85
Ca	4.57
Ti	0.55
Fe	4.90

(iv) Limestone Powder (LSP)

The limestone (LSP) used in the research was obtained from Abu-Hadriyah, a place in the eastern province of Saudi Arabia. Its specific gravity is 2.60 with light yellow color (Figure 3-4). Its chemical composition is shown in (Table 3-4).

Figure 3-4: Local Limestone Powder (LSP) Material

Table 3-4: Chemical Composition of the Used Limestone Powder (LSP) Material

Component	Weight %
CaO	45.70
SiO_2	11.79
Al_2O_3	2.17
Fe_2O_3	0.68
K_2O	0.84
MgO	1.80
Na_2O	1.72
$Na_2O + 0.658\ K_2O$	2.27
Loss on Ignition	35.10
Moisture	0.20

3.2.2 Alkaline Chemicals used for Activation

(i) Sodium Hydroxide

The sodium hydroxide (NaOH) used in this research was in the solid pellets form with white color and no odor (Figure 3-5). Its specific gravity was 2.13.

Figure 3-5: Sodium Hydroxide (NaOH) Pellets

(ii) Potassium Hydroxide

The potassium hydroxide (KOH) used in this research was in the solid hemispheres form with white color and no odor (Figure 3-6). Its specific gravity was 2.044.

Figure 3-6: **Potassium Hydroxide (KOH) Pellets**

(iii) Sodium Silicate Solution

The sodium silicate solution (Na_2SiO_3) used in this research was in the liquid form. It was colorless without odor (Figure 3-7). Its specific gravity was 1.52 with viscosity of 600 centipoise.

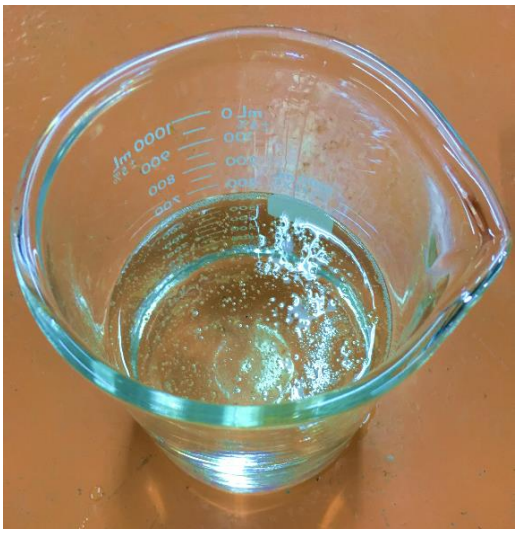

Figure 3-7: Sodium Silicate Solution (Na_2SiO_3)

3.2.3 Fine Aggregate

Local fine dune sand was used as fine aggregate. It was brought from eastern region in Saudi Arabia. The specific gravity and water absorption of fine aggregate were 2.56 and 0.4%, respectively. Table 3-5 shows the gradation of used fine aggregate.

Table 3-5: Gradation of Fine Aggregate

ASTM Sieve #	Percent passing
8	100
16	100
30	95
50	42
100	3.5
200	2.0

3.2.4 Coarse Aggregates

Crushed limestone rocks were used as coarse aggregates in this study. They were brought from Riyadh Road in Saudi Arabia. The coarse aggregate had a maximum aggregate size of 0.5 inch. Its specific gravity was 2.60 and its water absorption was 1.10 %. Table 3-6 shows the gradation of used coarse aggregate.

Table 3-6: Gradation of Coarse Aggregate

Sieve opening	Percent passing
¾ in	100
½ in	65
3/8 in	40
3/16 in	10
3/32 in	0

3.2.5 Superplasticizer (SP)

The superplasticizer used in this study was Glenium ® ACE 456 (Figure 3-8). Its technical data is shown in Table 3-7.

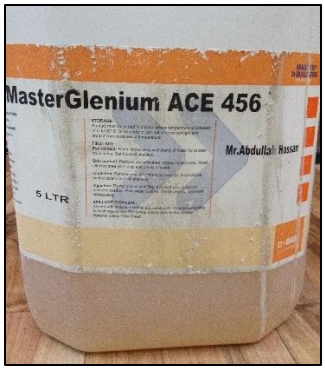

Figure 3-8: Glenium ® ACE 456

Table 3-7: Technical Data of Glenium ® ACE 456

Appearance and Form	Whitish to Light Brownish Liquid
Specific Gravity @ 25°C	1.060
pH-Value @ 25°C	4-7
Chloride Ion Content	≤ 0.01%
Alkali Content (Na_2O Equivalent %)	< 3%

3.2.6 Mixing Water

Potable water was used for mixing the ingredients of the geopolymer concrete mixtures. Distilled water was used to prepare the alkaline solutions to the specified molarities.

3.3 Design of Geopolymer Concrete Trial Mixtures

Following key parameters were considered as variables to design different series of the trial mixtures of geopolymer concrete:

- Type of cementitious materials (Portland cement, natural pozzolan, kaolin, and limestone powder),
- Type of alkali activators (sodium hydroxide and potassium hydroxide),
- Sodium silicate to alkali ratios (Na_2SiO_3/NaOH and Na_2SiO_3/KOH ratios).

The total cementitious materials content and fine/total aggregate ratio were kept constant with values of 480 kg/m^3 and 0.40 (by mass), respectively, for all trial mixtures. The optimum quantities of water and superplasticizer were obtained through several trials.

Total 54 different trial mixes were considered in this study. 18 trial mixtures belonged to each of the alternative cementitious materials including natural pozzolan, kaolin, and

limestone powder with and without OPC as secondary binder. Three different Na_2SiO_3/NaOH and Na_2SiO_3/KOH ratios of 4.0, 2.5 and 1.0 (by mass) were considered for each group of the cementitious materials, as shown in Table 3-8.

Table 3-8: Details of Cementitious Materials and Alkaline Activators Ratios for Trial Mixtures

Mixture Ingredients	Cementitious Materials		Alkaline Activator Ratio						No. of Trial Mixtures
	Primary Binder (by mass)	Secondary Binder (by mass)	$\frac{Na_2SiO_3}{NaOH}$			$\frac{Na_2SiO_3}{KOH}$			
Natural pozzolan (NP) Mixtures	NP (100, 90, 85%)	OPC (0, 10, 15%)	4.0	2.5	1.0	4.0	2.5	1.0	18
Kaolin Mixtures	Kaolin (100, 85, 70%)	OPC (0, 15, 30%)	4.0	2.5	1.0	4.0	2.5	1.0	18
Limestone Powder (LSP) Mixtures	LSP (100, 85, 70%)	OPC (0, 15, 30%)	4.0	2.5	1.0	4.0	2.5	1.0	18

The total amount of the alkaline materials (i.e., Na_2SiO_3 + NaOH or Na_2SiO_3 + KOH) was kept constant at 252 kg/m^3 which was optimized through several trials. The amounts of NaOH, and KOH were calculated for 16 Molar. The quantities of alkaline materials (Na_2SiO_3, NaOH, and KOH) corresponding to Na_2SiO_3/NaOH and Na_2SiO_3/KOH ratios of 4.0, 2.5 and 1.0 are given in Table 3-9 for producing 1 m^3 of geopolymer concrete mixture.

Table 3-9: Alkaline Material Content for 1 m^3 of Geopolymer Concrete Mixtures

Alkaline Material	Alkaline Material Content, kg					
	$\frac{Na_2SiO_3}{NaOH} = 4$	$\frac{Na_2SiO_3}{NaOH} = 2.5$	$\frac{Na_2SiO_3}{NaOH} = 1$	$\frac{Na_2SiO_3}{KOH} = 4$	$\frac{Na_2SiO_3}{KOH} = 2.5$	$\frac{Na_2SiO_3}{KOH} = 1$
NaOH (16 M)	50	72	122	0	0	0
KOH (16 M)	0	0	0	50	72	122
Na_2SiO_3	202	180	130	202	180	130

Design of the trial mixtures (i.e., mixture proportioning) consisted of the calculation of weights of the constituent materials for one cubic meter of each of the 54 trial mixtures of geopolymer concrete was accomplished using absolute volume method.

3.3.1 Proportions of Natural pozzolan-Based Trial Mixtures

Table 3-10 shows the weight of the constituent materials for the first nine natural pozzolan-based geopolymer concrete trial mixtures, which were activated by sodium hydroxide (NaOH). Whereas, Table 3-11 shows the weight of constituent materials for the other nine trial mixes, which were activated by potassium hydroxide (KOH).

Table 3-10: Weights of The Constituent Materials for 1 m^3 of Natural pozzolan-Based Geopolymer Concrete Trial Mixtures (Activated by Sodium Hydroxide, NaOH)

Mixture ID	Cement Type I kg	Natural pozzolan kg	Coarse Aggregate kg	Sand kg	Extra Water Kg	Super-plasticizer Kg	Na_2SiO_3 kg	NaOH kg
NP-M 1	0	480	964	643	12	9.6	202	50
NP-M 2	48	432	965	643	12	9.6	202	50
NP-M 3	72	408	966	644	12	9.6	202	50
NP-M 4	0	480	966	644	12	9.6	180	72
NP-M 5	48	432	967	645	12	9.6	180	72
NP-M 6	72	408	968	645	12	9.6	180	72
NP-M 7	0	480	971	647	12	9.6	130	122
NP-M 8	48	432	972	648	12	9.6	130	122
NP-M 9	72	408	972	648	12	9.6	130	122

Table 3-11: Weights of The Constituent Materials for 1 m^3 of Natural pozzolan-Based Geopolymer Concrete Trial Mixtures (Activated by Sodium Hydroxide, KOH)

Mixture ID	Cement Type I kg	Natural pozzolan kg	Coarse Aggregate kg	Sand kg	Extra Water Kg	Super-plasticizer kg	Na_2SiO_3 kg	KOH kg
NP-M 10	0	480	970	647	12	9.6	202	50
NP-M 11	48	432	971	647	12	9.6	202	50
NP-M 12	72	408	972	648	12	9.6	202	50
NP-M 13	0	480	975	650	12	9.6	180	72
NP-M 14	48	432	976	650	12	9.6	180	72
NP-M 15	72	408	976	651	12	9.6	180	72
NP-M 16	0	480	985	657	12	9.6	130	122
NP-M 17	48	432	986	657	12	9.6	130	122
NP-M 18	72	408	987	658	12	9.6	130	122

3.3.2 Proportions of Kaolin-Based Trial Mixtures

Table 3-12 shows the weight of the constituent materials for the first nine kaolin-based geopolymer concrete trial mixtures, which were activated by sodium hydroxide (NaOH). Table 3-13 shows the constituent materials for the other nine kaolin-based geopolymer concrete trial mixtures, which were activated by potassium hydroxide.

Table 3-12: Weights of The Constituent Materials for 1 m^3 of Kaolin-Based Geopolymer Concrete Trial Mixtures (Activated by Sodium Hydroxide, NaOH)

Mixture ID	Cement Type I kg	Kaolin kg	Coarse Aggregate kg	Sand kg	Extra Water Kg	Super-plasticizer kg	Na_2SiO_3 kg	NaOH kg
Kaolin-M1	0	480	898	598	36	14.4	202	50
Kaolin-M2	72	408	901	601	36	14.4	202	50
Kaolin-M3	144	336	903	602	36	14.4	202	50
Kaolin-M4	0	480	900	600	36	14.4	180	72
Kaolin-M5	72	408	903	602	36	14.4	180	72
Kaolin-M6	144	336	905	603	36	14.4	180	72
Kaolin-M7	0	480	904	603	36	14.4	130	122
Kaolin-M8	72	408	908	605	36	14.4	130	122
Kaolin-M9	144	336	909	606	36	14.4	130	122

Table 3-13: Weights of The Constituent Materials for 1 m^3 of Kaolin-Based Geopolymer Concrete Trial Mixtures (Activated by Sodium Hydroxide, KOH)

Mixture ID	Cement Type I kg	Kaolin kg	Coarse Aggregate kg	Sand kg	Extra Water Kg	Super-plasticizer kg	Na_2SiO_3 kg	KOH kg
Kaolin-M10	0	480	903	602	36	14.4	202	50
Kaolin-M11	72	408	907	605	36	14.4	202	50
Kaolin-M12	144	336	909	606	36	14.4	202	50
Kaolin-M13	0	480	908	605	36	14.4	180	72
Kaolin-M14	72	408	912	608	36	14.4	180	72
Kaolin-M15	144	336	913	609	36	14.4	180	72
Kaolin-M16	0	480	918	612	36	14.4	130	122
Kaolin-M17	72	408	922	615	36	14.4	130	122
Kaolin-M18	144	336	924	616	36	14.4	130	122

3.3.3 Properties of Limestone Powder-Based Trial Mixtures

Table 3-14 shows the constituent materials for the first nine limestone powder-based geopolymer concrete trial mixtures, which were activated by sodium hydroxide (NaOH). Table 3-15 shows the other nine trial mixes that were activated by potassium hydroxide (KOH).

Table 3-14: Weights of The Constituent Materials for 1 m^3 of Limestone Powder-Based Geopolymer Concrete Trial Mixtures (Activated by Sodium Hydroxide, NaOH)

Mixture ID	Cement Type I kg	Limestone Powder kg	Coarse Aggregate kg	Sand kg	Extra Water Kg	Super-plasticizer kg	Na_2SiO_3 kg	NaOH kg
LSP-M 1	0	480	866	577	48	14.4	202	50
LSP-M 2	72	408	871	581	48	14.4	202	50
LSP-M 3	144	336	873	582	48	14.4	202	50
LSP-M 4	0	480	868	579	48	14.4	180	72
LSP-M 5	72	408	873	582	48	14.4	180	72
LSP-M 6	144	336	875	584	48	14.4	180	72
LSP-M 7	0	480	872	582	48	14.4	130	122
LSP-M 8	72	408	877	585	48	14.4	130	122
LSP-M 9	144	336	880	587	48	14.4	130	122

Table 3-15: Weights of The Constituent Materials for 1 m^3 of Limestone Powder-Based Geopolymer Concrete Trial Mixtures (Activated by Sodium Hydroxide, KOH)

Mixture ID	Cement Type I kg	Limestone Powder kg	Coarse Aggregate kg	Sand Kg	Extra Water Kg	Super-plasticizer kg	Na_2SiO_3 kg	KOH kg
LSP-M 10	0	480	872	581	48	14.4	202	50
LSP-M 11	72	408	877	585	48	14.4	202	50
LSP-M 12	144	336	879	586	48	14.4	202	50
LSP-M 13	0	480	877	584	48	14.4	180	72
LSP-M 14	72	408	881	588	48	14.4	180	72
LSP-M 15	144	336	884	589	48	14.4	180	72
LSP-M 16	0	480	887	591	48	14.4	130	122
LSP-M 17	72	408	892	595	48	14.4	130	122
LSP-M 18	144	336	894	596	48	14.4	130	122

3.4 Preparation of Specimens of Geopolymer Concrete Mixtures

The hydroxide solutions including sodium hydroxide (NaOH) and potassium hydroxide (KOH) were prepared using distilled water, both having a concentration of 16 Molars. These alkaline solutions were kept at room environment (22° C) for 24 hours before mixing them separately with the sodium silicate, Na_2SiO_3 (alkaline grade) solution and the designed quantity of extra water. Then, they were thoroughly mixed for 30 minutes using a stirrer device, as shown in Figure 3-9.

Figure 3-9: Stirrer Device

The dry constituents were charged to an electric mixer, as shown in Figure 3-10. During the dry mixing, 50% of the liquids quantity was added and mixing was carried. Then, the remaining amount of liquids was added followed by addition of superplasticizer to the mixture. The mixer continued to run until a homogenous mixture was obtained. Then, the mixture was casted in molds using the vibration table.

Figure 3-10: Electric Mixer

After casting, the specimens were cured in room environment (22° C) for 24 hours while keeping them in the molds. The specimens after demolding were kept inside an oven for 7 days at (60° C) for heat curing. To minimize the loss of water from the specimens during heat curing in the oven, the specimens were sealed using plastic sheets, as shown in Figure 3-11.

After the heat curing period was finished, the test specimens were kept outside the oven to cool down to room temperature prior to testing.

Figure 3-11: Heat Curing for Geopolymer Specimens

3.5 Details of Test Standards and Specimens

The details of test standards and test specimens used for evaluating mechanical properties, water absorption, acid resistance, thermal resistance, chloride permeability and drying shrinkage characteristics are shown in Table 3-16.

Table 3-16: Details of Test Standard for Evaluation of the Hardened Properties of Geopolymer Concrete Mixtures

Property	Test Standard	Specimen Size
a. Preliminary Study of Trial Mixes		
Compressive Strength	ASTM C 39	50 mm cube
b. Detailed Study of Selected Mixes		
Splitting Tensile Strength	ASTM C 496	75 x150 mm cylinder
Elastic Modulus	ASTM C 469	75 x150 mm cylinder
Water Absorption	ASTM C 642	50 mm cube
Acid Resistance	ASTM C 267	50 mm cube
Fire Resistance	ASTM E 119	50 mm cube
Rapid Chloride Permeability	ASTM C 1202	75 x 50 mm disks
Drying Shrinkage	ASTM C 531	250 x 50 x50 mm prisms

The preliminary phase of study consisted of performing the compressive strength test for all 54 trial mixtures. Based on the achievement of compressive strength testing, eight mixtures of geopolymer concrete (four natural pozzolan, two kaolin and two limestone powder-based mixtures) were selected for the detailed study involving the testing of the specimens to determine mechanical, water absorption, acid resistance, thermal resistance, chloride permeability, and drying shrinkage properties.

3.6 Preliminary Evaluation of Geopolymer Concrete Trial Mixtures

Cubes with 50 mm size were casted for determining the compressive strength according to ASTM C 39 after 7 days of heat curing. The testing was performed using a hydraulic type of an automatic compressive testing machine, as shown in Figure 3-12. A constant rate of 1.5 kN/s was maintained while applying the compressive load. The load was noted corresponding to the failure of specimen. Strength was determined by dividing the failure load by the cross-sectional area of the specimens. The average of the compressive strength of three tested specimens for each mixture was taken as the representative value.

Figure 3-12: Automatic Compressive Testing Machine

3.7 Detailed Evaluation of the Selected Geopolymer Concrete Mixtures

3.7.1 Splitting Tensile Strength Test

75 mm x 150 mm cylinders were used for conducting splitting tensile strength test according to ASTM C 496 after 7 days of heat curing. The test was accomplished using an automatic hydraulic type splitting tensile testing machine, as shown in Figure 3-13.

Figure 3-13: Automatic Splitting Tensile Testing Machine.

The load was applied at a constant rate of 0.4 kN/s until failure of specimen. Three specimens were tested for each mixture. The average of three failure loads for three specimens of the same mixtures was considered to calculate splitting tensile strength using the following formula:

$$f_t = \frac{2P}{\pi l d}$$

Where:

f_t = splitting tensile strength (MPa); P = average failure load (N); l = specimen length (mm); and d = specimen diameter (mm).

3.7.2 Modulus of Elasticity Test

75 mm x 150 mm concrete cylinders were used to conduct the modulus of elasticity test. The test was conducted according to ASTM C 469 after 7 days of heat curing of the specimens. The specimens were tested using the same automatic compressive testing machine that was used for compressive strength. However, a frame of gauge containing two linear variable displacement transducers (LVDTs) was attached to the specimen, as shown in Figure 3-14.

Figure 3-14: Test Setup for Determining Elastic Modulus

The load was applied at a constant rate of 0.5 kN/s. The load-deformation data were recorded using a connected data logger. Then, using the stress-strain curves, elastic modulus was calculated using the following formula:

$$E = \frac{S_2 - S_1}{\epsilon_2 - 0.000050}$$

Where:

E = Elastic Modulus (MPa); S_2 = Stress (MPa) equivalent to 40 % of ultimate load; S_1 = Stress (MPa) equivalent to a longitudinal strain of 0.000050; ϵ_2 = Longitudinal strain created by S_2.

3.7.3 Water Absorption Test

The water absorption test was performed using cubical specimens of 50 mm size after heat curing for 7 days in accordance to ASTM C 642. After heat curing, the specimens were dried at a temperature of 105 ° C for 24 hours in oven, as shown in Figure 3-15.

Figure 3-15: Oven Heating for Determining Water Absorption

After drying, the specimens were allowed to cool to room temperature. Then, the average of three weights for each mixture were recorded as (W_1). Then, the specimens were immersed in water bath at room temperature for 48 hours, as shown in Figure 3-16.

Figure 3-16: Water Bath for Determining Water Absorption

After allowing specimens to absorb water for 48 hours, they were removed from the water bath and the average of three weights for each mixture (W_2) was recorded after removing the surface water using cloth.

The percentage water absorption was calculated as follows:

$$\text{Water Absorption } (\%) = (W_2 - W_1) \times 100 / W_1$$

Where:

W_1 = dried weight of specimen.

W_2 = wet weight of specimen.

3.7.4 Acid Resistance Test

The hydrochloric (HCl) acid solution with 3% concentration was used for exposing the cubical specimens of 50 mm size for 28 days to assess the acid resistance of the selected geopolymer concrete mixtures. For this purpose, the specimens after 7 days of heat curing were immersed in HCl solution for 28 days, as shown in Figure 3-17.

Figure 3-17: Specimens Immersed in (HCl) Solution for Determining Acid Resistance

After 28 days of acid exposure, the exposed specimens were removed from the acid container and tested for their compressive strength. Then, the residual average compressive strength for each mixture was calculated. Three specimen were tested for each mixture.

3.7.5 Thermal Resistance Test

The thermal resistance of the selected concrete mixtures was assessed by exposing them to an elevated temperature of 300 °C for 1 hour, simulating the fire conditions. For this purpose, cubical specimens of 50 mm size were used. After 7 days of heat curing, the specimens were exposed to 300 °C in a furnace, as shown in Figure 3-18.

Figure 3-18: Specimens Burned at 300 °C for Determining Thermal Resistance

After the exposure period, the tested specimens were removed from the furnace and left to cool to room temperature prior to compression testing. Then, the specimens were tested for their compressive strengths and their average residual strengths were calculated. Three specimens for each mixture were used to assess the thermal resistance.

3.7.6 Rapid Chloride Permeability Test

The rapid chloride permeability (RCP) test for the selected geopolymer concrete specimens was determined according to ASTM C1202 after 7 days of heat curing. For this purpose,

75 x 150 mm cylindrical specimens after 7 days of heat curing were cut into disks of 50 mm thick. Then, disks were coated on their curved surface using epoxy, as shown in Figure 3-19. Vacuum desiccation for 4 hours was carried. Then, the specimens were left in water in the desiccator and kept saturated for 18 hours, as shown in Figure 3-20.

Figure 3-19: Coating Specimens' Curved Surface with Epoxy for RCP Test

Figure 3-20: Vacuum Desiccator

As shown in Figure 3-21, the test setup consisted of two half-cells. One cell was filled with 3.0 % NaCl solution and the other with 0.3 M NaOH solution. The specimen was fitted between the half-cells. Current was allowed to pass through the specimens under a potential difference of 10 V DC. It was not possible to maintain a higher potential difference because the testing machine stopped immediately when a high potential difference was used. This

is due to the high alkalinity of geopolymer concrete. The current passing over a time duration of six hours was recorded using a data logger. Finally, the total charge passing through the specimens were calculated using the current versus time curve.

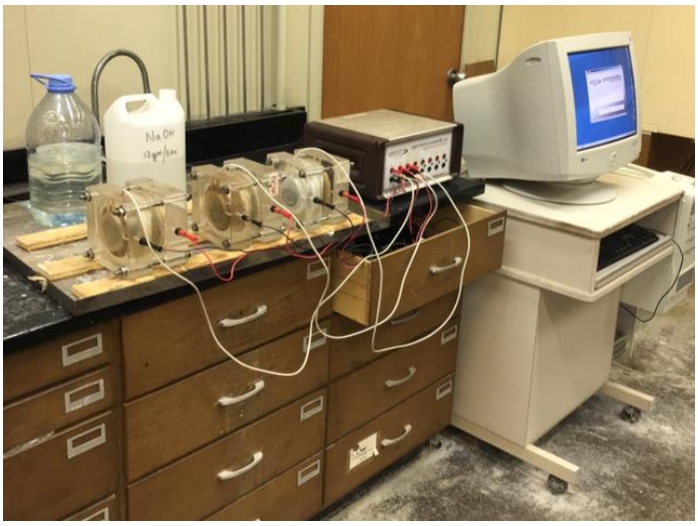

Figure 3-21: The RCP test's Setup

3.7.7 Drying Shrinkage Test

Prism concrete specimens with 250 x 50 x 50 mm dimensions were used to measure the drying shrinkage of the selected geopolymer concrete mixtures. The drying shrinkage test was conducted according to ASTM C 531 after heat curing for 7 days. The setup used for monitoring the shrinkage is shown in Figure 3-22.

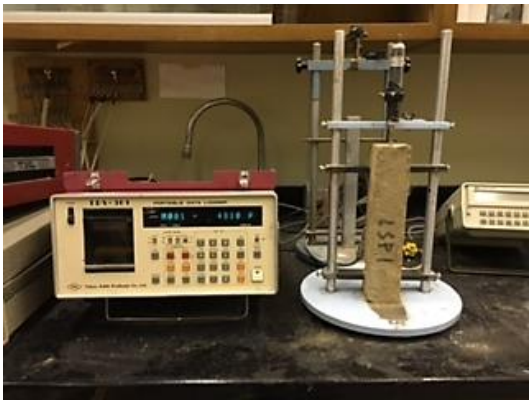

Figure 3-22: Drying Shrinkage test's Setup

CHAPTER 4

RESULTS & DISCUSSIONS

4.1 Results of Preliminary Evaluation of Geopolymer Concrete Trial Mixtures

The results of the compressive strength test, which was conducted for all 54 different trial mixtures of geopolymer concrete after heat curing for 7 days, are discussed in the following sections.

4.1.1 Compressive Strength of NP-Based Mixtures Activated by NaOH

The plots of compressive strengths of NP-based mixtures activated by NaOH and heat-cured for 7 are shown in Figure 4-1.

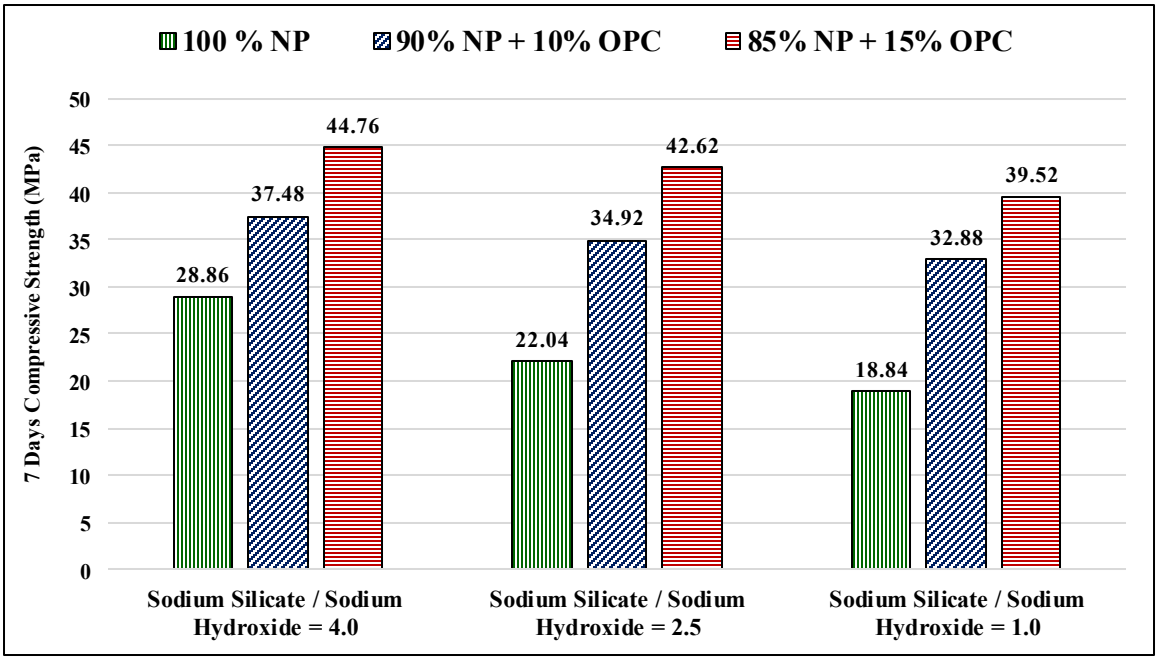

Figure 4-1: Compressive Strengths of NP-Based Mixtures Activated by NaOH

It can be clearly seen from Figure 4-1 that both factors (Na_2SiO_3/NaOH ratio and NP content) significantly affect the compressive strength. Strength is found to be higher at lower NP content and higher Na_2SiO_3/NaOH ratio. Among all nine combinations of NP content and Na_2SiO_3/NaOH ratio, a maximum strength of 44.76 MPa is achieved at a NP content of 85% and Na_2SiO_3/NaOH ratio of 4.0. The minimum strength of 18.84 MPa was noted at a NP content of 100% and Na_2SiO_3/NaOH ratio of 1.0. Therefore, a suitable combination of Na_2SiO_3/NaOH ratio and NP content can be selected to achieve a target strength between minimum and maximum values. It can be further noted that except one mixture, all other eight NP-based mixtures activated by NaOH have compressive strength more than 20 MPa, satisfying the strength requirement of a structural concrete.

The results of the analysis of variance (ANOVA), conducted using the compressive strength results of all nine trial NP-based mixtures activated by NaOH, are shown in Table 4-1. As it can be observed from Table 4-1, both the Na_2SiO_3/NaOH ratio and the NP content are found to be significant factors affecting compressive strength.

Table 4-1: ANOVA of NP-Based Mixtures Activated by NaOH

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	F_{cr}	*Significance criteria* P< 0.05 and F > F_{cr}
Na_2SiO_3/NaOH ratio	66.3	2	33.1	12.5	0.01898	6.94	**Significant**
NP content	555.3	2	277.6	104.8	0.00035	6.94	**Significant**
Error	10.5	4	2.6				
Total	632.2	8					

Equation for the compressive strength obtained through linear regression is given as:

$$f_c' = 143.35 + 2.21AR - 1.26NP \qquad (R^2 = 0.98)$$

Where:

f_c' = compressive strength (MPa)

AR = Na_2SiO_3/NaOH ratio (by mass)

NP = Natural pozzolan content (%)

A very high value of correlation coefficient (R^2) indicates an excellent correlation between the compressive strength and the key parameters (NP content and Na_2SiO_3/NaOH ratio) affecting the compressive strength.

4.1.2 Compressive Strength of NP-Based Mixtures Activated by KOH

The plots of compressive strengths of NP-based mixtures activated by KOH and heat-cured for 7 are shown in Figure 4-2.

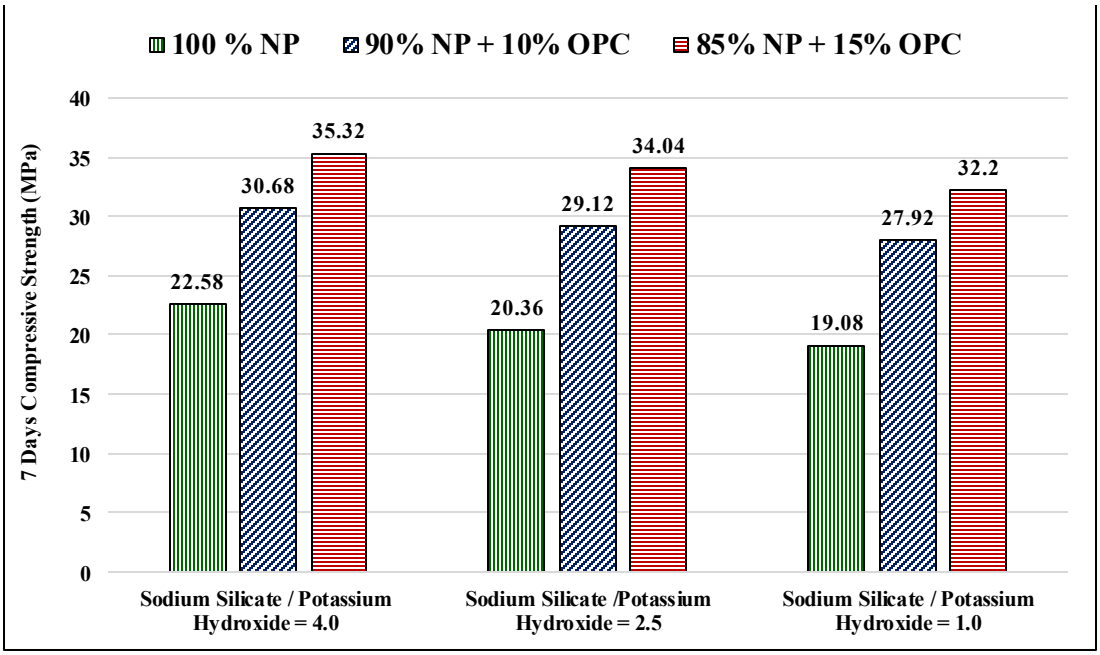

Figure 4-2: Compressive Strengths of NP-Based Mixtures Activated by KOH

Both factors (Na_2SiO_3/NaOH ratio and NP content) significantly affect the compressive strength, as can be observed from Figure 4-2. Strength is found to be higher at lower NP content and higher Na_2SiO_3/NaOH ratio. However, NaOH is more effective as an activator than KOH as can be observed from Figures 4-1 and 4-2. Among all nine combinations of

NP content and Na_2SiO_3/KOH ratio, a maximum strength of 35.32 MPa is achieved at a NP content of 85% and Na_2SiO_3/KOH ratio of 4.0 as shown in Figure 4-2. The minimum strength of 19.08 MPa was noted at a NP content of 100% and Na_2SiO_3/KOH ratio of 1.0. Therefore, a suitable combination of Na_2SiO_3/KOH ratio and NP content can be selected to achieve a target strength between minimum and maximum values. It can be further noted that except one mixture, all other eight NP-based mixtures activated by KOH have compressive strength more than 20 MPa, satisfying the strength requirement of a structural concrete.

Table 4-2 shows the results of the analysis of variance (ANOVA), conducted using the compressive strength results of nine trial NP-based mixtures activated by KOH. As it can be seen from Table 4-2, both the Na_2SiO_3/KOH ratio and the NP content are found to be significant factors affecting compressive strength.

Table 4-2: ANOVA of NP-Based Mixtures Activated by KOH

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	F_{cr}	*Significance criteria* P< 0.05 and F > F_{cr}
Na_2SiO_3/KOH ratio	14.7	2	7.3	89.7	0.000476	6.94	**Significant**
NP content	268.4	2	134.2	1638.3	1.49×10^{-6}	6.94	**Significant**
Error	0.3	4	0.08				
Total	283.4	8					

Equation for the compressive strength obtained through linear regression is given as:

$$f_c' = 105.57 + 1.04AR - 0.88NP \qquad (R^2 = 0.99)$$

Where:

f_c' = compressive strength (MPa)

AR = Na_2SiO_3/KOH ratio (by mass)

NP = Natural pozzolan content (%)

A very high value of correlation coefficient (R^2) indicates an excellent correlation between the compressive strength and the key parameters (NP content and Na_2SiO_3/KOH ratio) affecting the compressive strength.

4.1.3 Compressive Strength of Kaolin-Based Mixtures Activated by NaOH

The plots of compressive strengths of kaolin-based mixtures activated by NaOH and heat-cured for 7 days are shown in Figure 4-3. For kaolin-based mixtures, only the kaolin content significantly affects the compressive strength. At a given Na_2SiO_3/NaOH ratio, the strength increases with decrease in kaolin content. The effect of Na_2SiO_3/NaOH ratio is found to be little to negligible. However, a Na_2SiO_3/NaOH ratio of 2.5 is found to be optimum, as can be seen from Figure 4-3. Among all nine combinations of kaolin content and Na_2SiO_3/NaOH ratio, a maximum strength of 16.84 MPa is achieved at a kaolin content of 70% and Na_2SiO_3/NaOH ratio of 2.5. The minimum strength of 2.72 MPa was noted at a kaolin content of 100% and Na_2SiO_3/NaOH ratio of 1.0. It can be further noted that none of the kaolin-based mixtures activated by NaOH achieved a minimum compressive strength of 20 MPa, required for being considered as structural concrete.

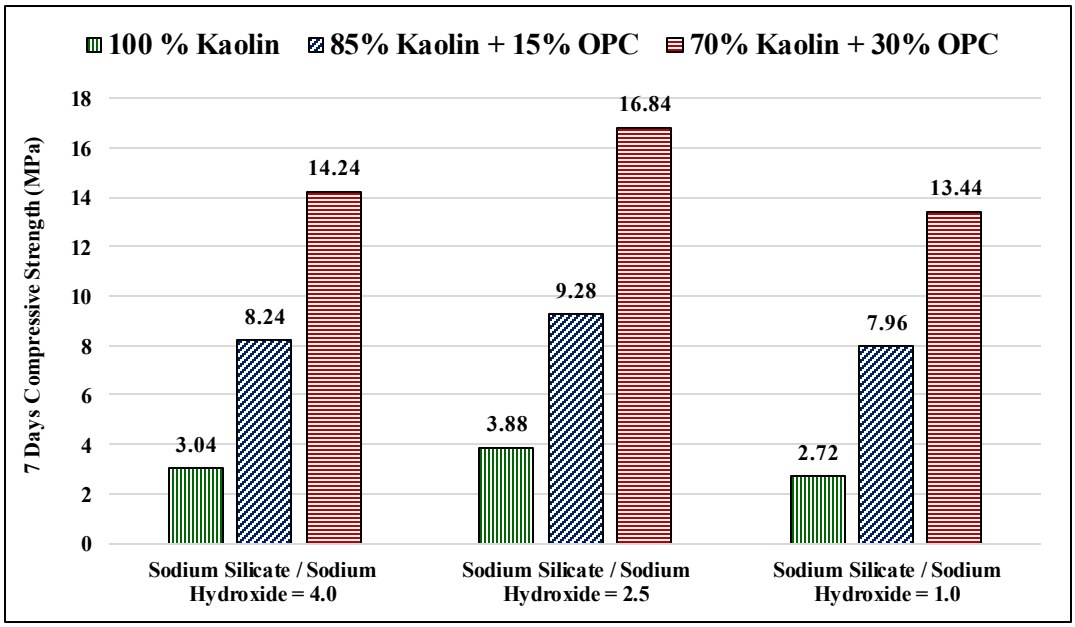

Figure 4-3: Compressive Strength of Kaolin-Based Mixtures (Activated by NaOH)

Table 4-3 shows the results of the analysis of variance (ANOVA), conducted using the compressive strength results of nine trial kaolin-based mixtures activated by NaOH. As it can be seen from Table 4-3, only the kaolin content is found to be significant factor affecting compressive strength. The effect of Na_2SiO_3/NaOH ratio is negligible as it has F-value and P-value both very close to the criteria for rejection of their effect.

Table 4-3: ANOVA of Kaolin-Based Mixtures Activated by NaOH

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	F_{cr}	*Significance criteria* P< 0.05 and F > F_{cr}
Na_2SiO_3/NaOH ratio	6.28	2	3.1	7.3	0.045944	6.94	**Negligible**
Kaolin content	203.3	2	101.7	237.0	7×10^{-5}	6.94	**Significant**
Error	1.7	4	0.4				
Total	211.3	8					

Equation for the compressive strength obtained through linear regression is given as:

$$f_c' = 41.4 + 0.16AR - 0.39K \qquad (R^2 = 0.96)$$

Where:

f_c' = compressive strength (MPa)

AR = Na_2SiO_3/NaOH ratio (by mass)

K = kaolin content (%)

A very high value of correlation coefficient (R^2) indicates an excellent correlation between the compressive strength and the key parameters (kaolin content and Na_2SiO_3/NaOH ratio) affecting the compressive strength.

4.1.4 Compressive Strength of Kaolin-Based Mixtures Activated by KOH

The plots of compressive strengths of kaolin-based mixtures activated by KOH and heat-cured for 7 days are shown in Figure 4-4

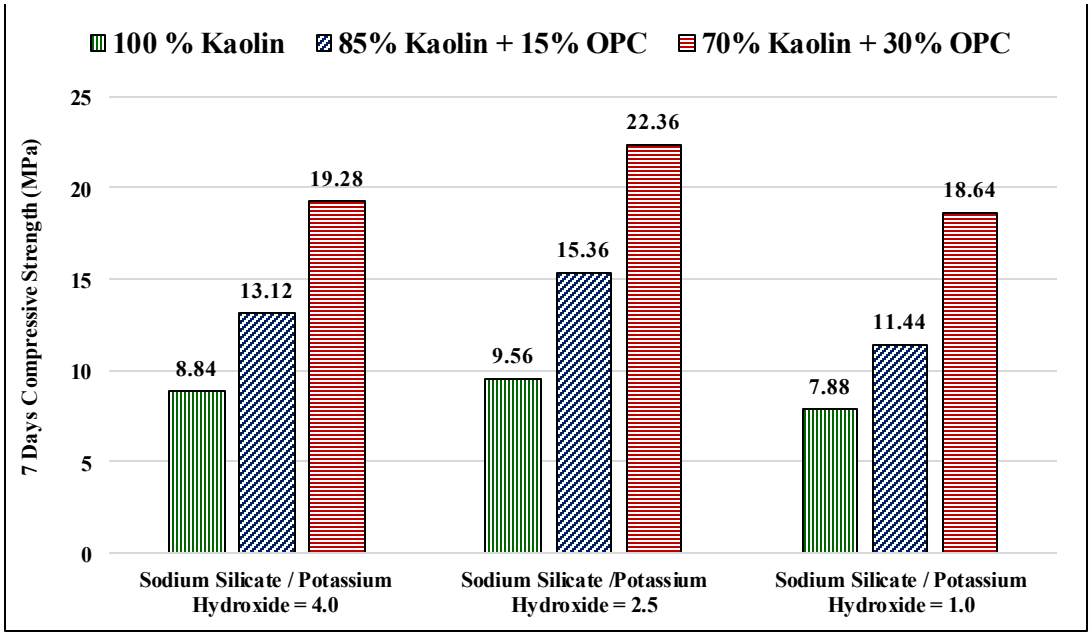

Figure 4-4: Compressive Strength of Kaolin-Based Mixtures (Activated by KOH)

Both the kaolin content and Na_2SiO_3/KOH ratio have effect on strength. However, a Na_2SiO_3/KOH ratio of 2.5 is found to be optimum, as can be seen from Figure 4-4. At a given Na_2SiO_3/KOH ratio, the strength increases with decrease in kaolin content. By

comparing the results shown in Figures 4-3 and 4-4, it can be noted that for kaolin-based mixtures the KOH is more effective as an activator than NaOH. Among all nine combinations of kaolin content and Na_2SiO_3/KOH ratio, a maximum strength of 22.36 MPa is achieved at a kaolin content of 70% and Na_2SiO_3/KOH ratio of 2.5. The minimum strength of 7.88 MPa was noted at a kaolin content of 100% and Na_2SiO_3/KOH ratio of 1.0. It can be further noted that except one mixture, none of the other eight kaolin-based mixtures activated by KOH have compressive strength more than 20 MPa. Table 4-4 shows the results of the analysis of variance (ANOVA), conducted using the compressive strength results of nine trial kaolin-based mixtures activated by KOH. The effect of kaolin content and Na_2SiO_3/KOH ratio on compressive strength can be stated as significant.

Table 4-4: ANOVA of Kaolin-Based Mixtures Activated by KOH

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	F_{cr}	*Significance criteria* P< 0.05 and F > F_{cr}
Na_2SiO_3/KOH ratio	14.9	2	7.4	13.7	0.01612	6.94	**Significant**
Kaolin content	195.2	2	97.6	180.1	0.00012	6.94	**Significant**
Error	2.2	4	0.5				
Total	212.2	8					

Equation for the compressive strength obtained through linear regression is given as:

$$f_c' = 45.25 + 0.36AR - 0.38K \qquad (R^2 = 0.92)$$

Where:

f_c' = compressive strength (MPa)

AR = Na_2SiO_3/KOH ratio (by mass)

K = Kaolin content (%)

A very high value of correlation coefficient (R^2) indicates an excellent correlation between the compressive strength and the key parameters (Kaolin content and Na_2SiO_3/KOH ratio) affecting the compressive strength.

4.1.5 Compressive Strength of Limestone-Based Mixtures Activated by NaOH

The plots of compressive strengths of limestone powder-based mixtures activated by NaOH and heat-cured for 7 days are shown in Figure 4-5.

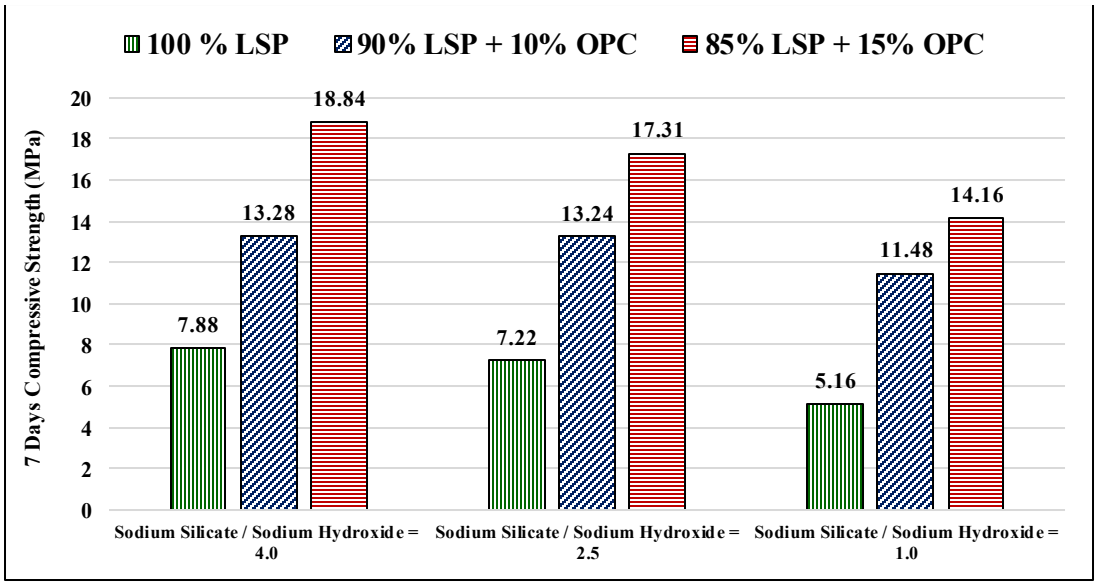

Figure 4-5: Compressive Strength (MPa) of Limestone Powder- Based Mixtures (Activated by NaOH)

It can be clearly seen from Figure 4-5 that limestone powder content strongly affects the compressive strength. The Na_2SiO_3/NaOH ratio has a lower effect on strength. Strength is found to be higher at lower limestone powder content and higher Na_2SiO_3/NaOH ratio. Among all nine combinations of limestone powder content and Na_2SiO_3/NaOH ratio, a maximum strength of 18.84 MPa is achieved at a limestone powder content of 85% and Na_2SiO_3/NaOH ratio of 4.0. The minimum strength of 5.16 MPa was noted at a limestone powder content of 100% and Na_2SiO_3/NaOH ratio of 1.0. It can be further noted that none

of limestone powder-based mixtures activated by NaOH have compressive strength more than 20 MPa, required for being considered as structural concrete.

Table 4-5 shows the results of the analysis of variance (ANOVA), conducted using the compressive strength results of nine trial LSP-based mixtures activated by NaOH. As it can be seen from Table 4-5, both the Na_2SiO_3/NaOH ratio and the LSP content are found to be significant factors affecting compressive strength. However, LSP content is clearly seen as strong factor.

Table 4-5: ANOVA of LSP-Based Mixtures Activated by NaOH

Source of Variation	*SS*	*Df*	*MS*	*F*	*P-value*	F_{cr}	*Significance criteria* P< 0.05 and F > F_{cr}
Na_2SiO_3/NaOH ratio	15.4	2	7.7	14.1	0.01536	6.94	**Significant**
LSP content	152.1	2	76.1	140.0	0.000198	6.94	**Significant**
Error	2.2	4	0.5				
Total	169.7	8					

Equation for the compressive strength obtained through linear regression is given as:

$$f_c' = 37.89 + 1.02AR - 0.33LSP \qquad (R^2 = 0.97)$$

Where:

f_c' = compressive strength (MPa)

AR = Na_2SiO_3/NaOH ratio (by mass)

LSP = limestone powder content (%)

A very high value of correlation coefficient (R^2) indicates an excellent correlation between the compressive strength and the key parameters (LSP content and Na_2SiO_3/NaOH ratio) affecting the compressive strength.

4.1.6 Compressive Strength of Limestone -Based Mixtures Activated by KOH

The plots of compressive strengths of Limestone Powder-based mixtures activated by KOH and heat-cured for 7 days are shown in Figure 4-6.

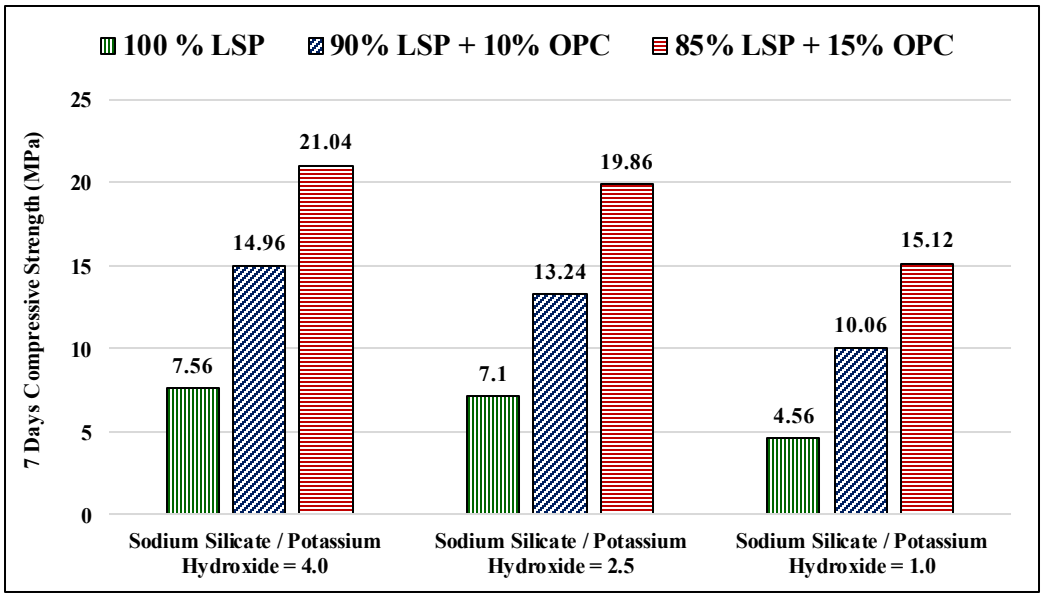

Figure 4-6: Compressive Strength (MPa) of Limestone Powder- Based Mixtures (Activated by KOH)

Both factors (Na_2SiO_3/KOH ratio and LSP content) significantly affect the compressive strength, as observed from Figure 4-6. Strength is found to be higher at lower LSP content and higher Na_2SiO_3/KOH ratio. However, the LSP-based mixtures activated by KOH achieved better strength than the LSP-based mixtures activated by NaOH, as evident from the comparison of test results shown in Figures 4-5 and 4-6. Among all nine combinations of LSP content and Na_2SiO_3/KOH ratio, a maximum strength of 21.04 MPa is achieved at a LSP content of 85% and Na_2SiO_3/KOH ratio of 4.0. The minimum strength of 4.56 MPa was noted at a LSP content of 100% and Na_2SiO_3/KOH ratio of 1.0. It can be further noted that except one mixture, none of the other eight LSP-based mixtures activated by KOH have compressive strength more than 20 MPa, required for being considered as a structural concrete.

Table 4-6 shows the results of the analysis of variance (ANOVA), conducted using the compressive strength results of nine trial LSP-based mixtures activated by KOH. As it can be seen from Table 4-6, both the Na_2SiO_3/KOH ratio and the LSP content are found to be significant factors affecting compressive strength.

Table 4-6: ANOVA of LSP-Based Mixtures Activated by KOH

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	F_{cr}	*Significance criteria* P< 0.05 and F > F_{cr}
Na_2SiO_3/KOH ratio	34.6	2	17.3	26.8	0.00482	6.94	**Significant**
LSP content	225.8	2	112.9	174.8	0.000128	6.94	**Significant**
Error	2.6	4	0.6				
Total	263.0	8					

Equation for the compressive strength obtained through linear regression is given as:

$$f_c' = 43.53 + 1.54AR - 0.41LSP \qquad (R^2 = 0.98)$$

Where:

f_c' = compressive strength (MPa)

AR = Na_2SiO_3/KOH ratio (by mass)

LSP = limestone powder content (%)

A very high value of correlation coefficient (R^2) indicates an excellent correlation between the compressive strength and the key parameters (LSP content and Na_2SiO_3/KOH ratio) affecting the compressive strength.

4.2 Results of Detailed Evaluation of Selected Mixtures

Out of 54 geopolymer concrete trial mixtures, eight were selected for detailed evaluation based on the results of the preliminary evaluation. From each group, mixtures were selected

based on highest compressive strength in the group. Details of the mixtures selected for detailed evaluation are presented in Table 4-7.

Table 4-7: Compressive Strength of Selected Geopolymer Concrete Mixes

Selected Mixture ID	Key Parameters	Compressive Strength (MPa)
SM 1	100% NP, $\frac{\text{Sodium Silicate}}{\text{soduim Hydroxide}} = 4.0$	28.86
SM 2	100% NP, $\frac{\text{Sodium Silicate}}{\text{potassium Hydroxide}} = 4.0$	22.58
SM 3	85% NP, $\frac{\text{Sodium Silicate}}{\text{soduim Hydroxide}} = 4.0$	44.76
SM 4	85% NP, $\frac{\text{Sodium Silicate}}{\text{potassium Hydroxide}} = 4.0$	35.32
SM 5	70% Kaolin, $\frac{\text{Sodium Silicate}}{\text{soduim Hydroxide}} = 2.5$	16.84
SM 6	70% Kaolin, $\frac{\text{Sodium Silicate}}{\text{potassium Hydroxide}} = 2.5$	22.36
SM 7	70% LSP, $\frac{\text{Sodium Silicate}}{\text{soduim Hydroxide}} = 4.0$	18.84
SM 8	70% LSP, $\frac{\text{Sodium Silicate}}{\text{potassium Hydroxide}} = 4.0$	21.04

The results of the detailed study for the selected geopolymer concrete mixtures was presented in this section and discussion was made regarding the performance of the selected mixtures in terms of compressive strength, splitting tensile strength, modulus of elasticity, water absorption, acid resistance, thermal resistance, rapid chloride permeability and drying shrinkage.

4.2.1 Compressive Strength

The compressive strengths of the eight selected mixtures, obtained by testing specimens after 7 days of heat curing, are shown in Figure 4-7.

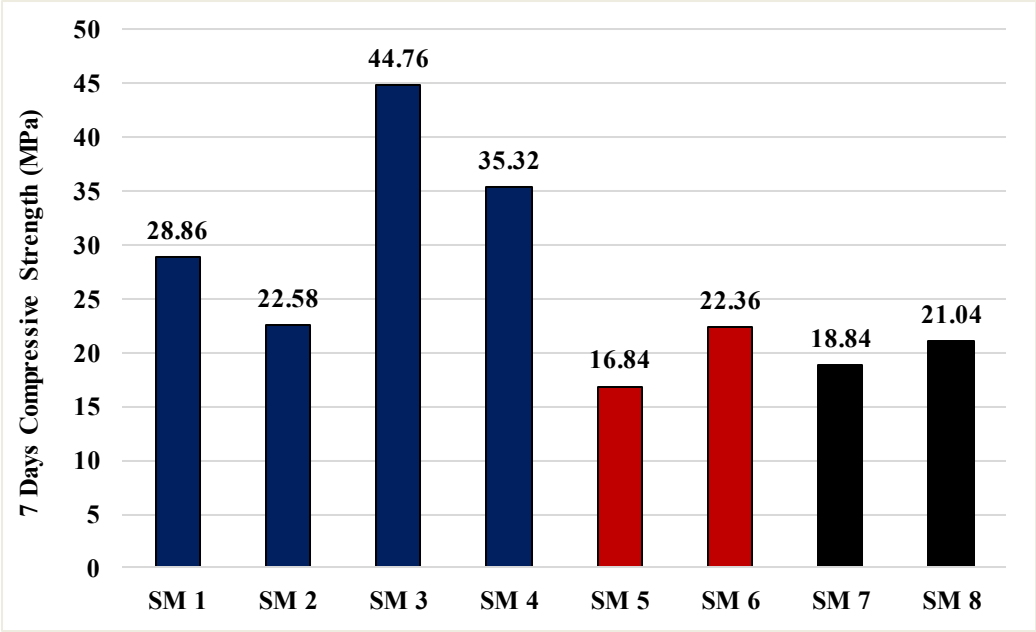

Figure 4-7: Compressive Strength of Selected Geopolymer Concrete Mixtures

The NP-based mixtures (SM3 treated by NaOH and SM4 treated by KOH) having 85% NP (with 15% Portland cement) showed more strength than the NP-based mixtures (SM1 treated by NaOH and SM2 treated by KOH) having 100% NP (no Portland cement). However, both SM1 and SM2 have strength above 20 MPa and therefore they can be used as structural concrete. The kaolin-based mixture SM5 treated by NaOH with strength less than 20 MPa does not qualify as a structural concrete. However, the other kaolin-based mixture SM6 treated by KOH with a strength of 22.36 MPa can be used as a structural concrete. Like the case of kaolin-based mixtures, the LSP-based mixture SM7 treated by NaOH with strength less than 20 MPa does not qualify as a structural concrete. However, the other LSP-based mixture SM8 treated by KOH with a strength of 21.04 MPa can be used as a structural concrete.

4.2.2 Splitting Tensile Strength

The splitting tensile strengths of the eight selected mixtures, obtained by testing specimens after 7 days of heat curing, are shown in Figure 4-8.

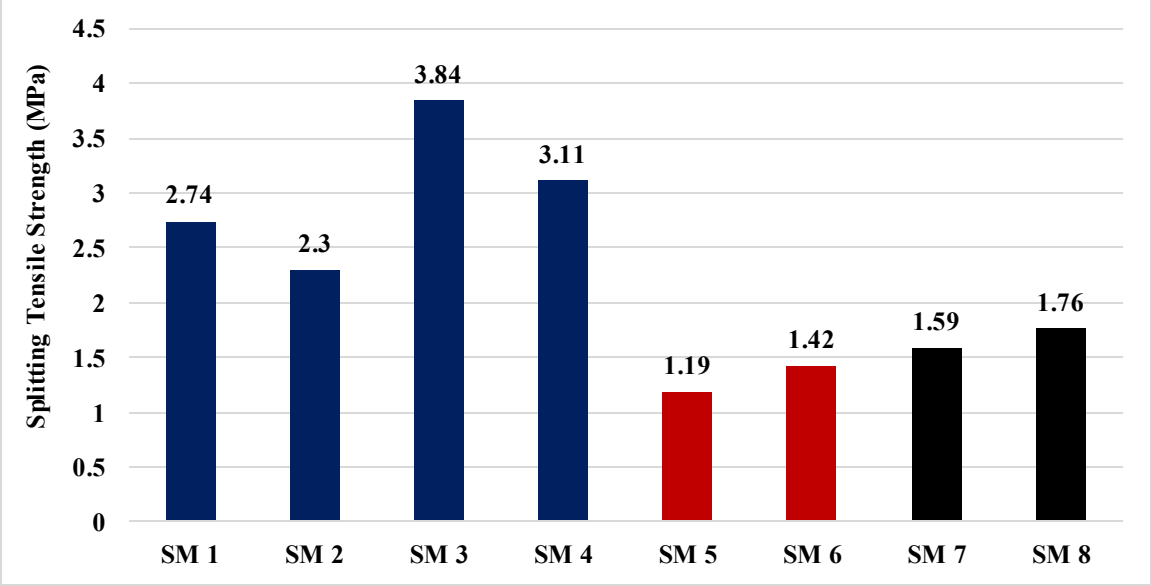

Figure 4-8: Splitting Tensile Strength of Selected Geopolymer Mixtures

The NP-based mixtures (SM3 treated by NaOH and SM4 treated by KOH) having 85% NP (with 15% Portland cement) showed more tensile strength than the NP-based mixtures (SM1 treated by NaOH and SM2 treated by KOH) having 100% NP (no Portland cement). However, both SM1 and SM2 have splitting tensile strength above 2 MPa, a minimum value for a normal structural concrete. The kaolin-based mixtures SM5 and SM6, treated by NaOH and KOH, respectively, have tensile strength less than a minimum value of 2 MPa. Like kaolin-based mixtures, LSP-based mixtures SM7 and SM8 also have splitting tensile strength less than 2 MPa.

A good correlation between compressive strength and splitting tensile strength for geopolymer concrete mixtures exists as shown in Figure 4-9.

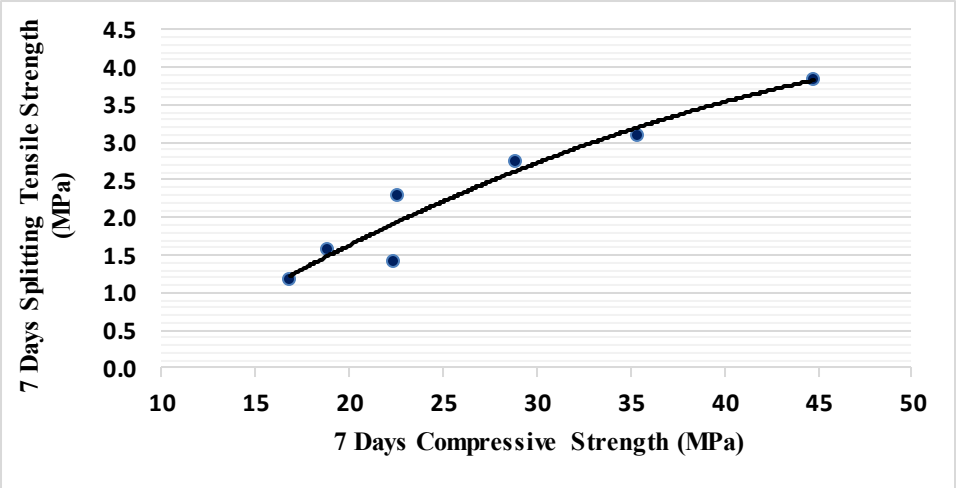

Figure 4-9: Correlation between Compressive Strength and Splitting Tensile Strength

4.2.3 Modulus of Elasticity

The stress-strain curves of the eight selected mixtures, obtained by testing specimens after 7 days of heat curing, are shown in Figures 4-10 through 4-17.

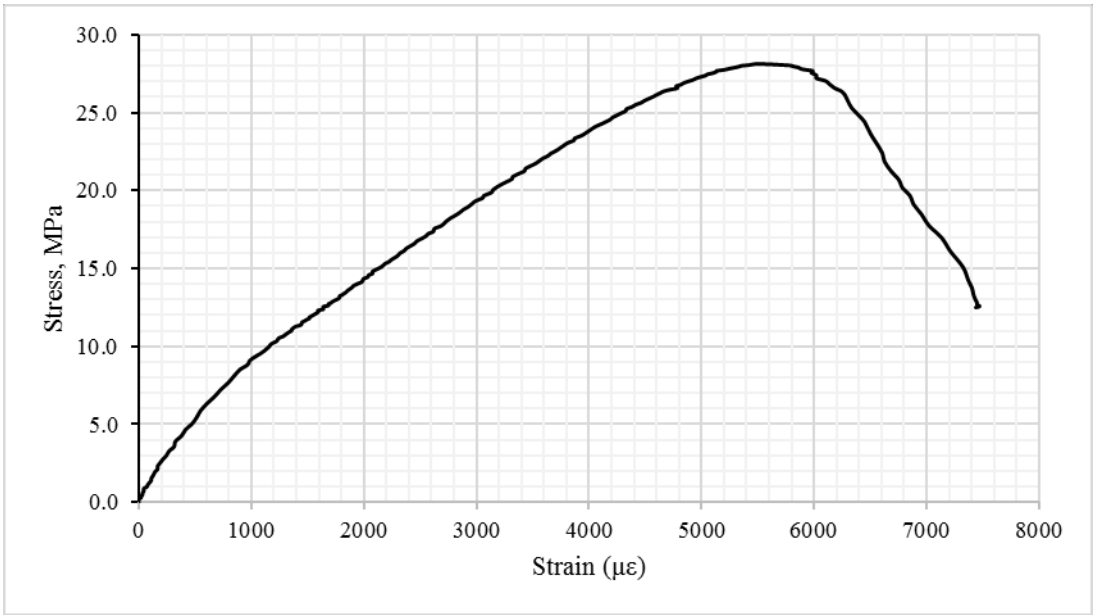

Figure 4-10: Stress - Strain Correlation for Mixture SM 1

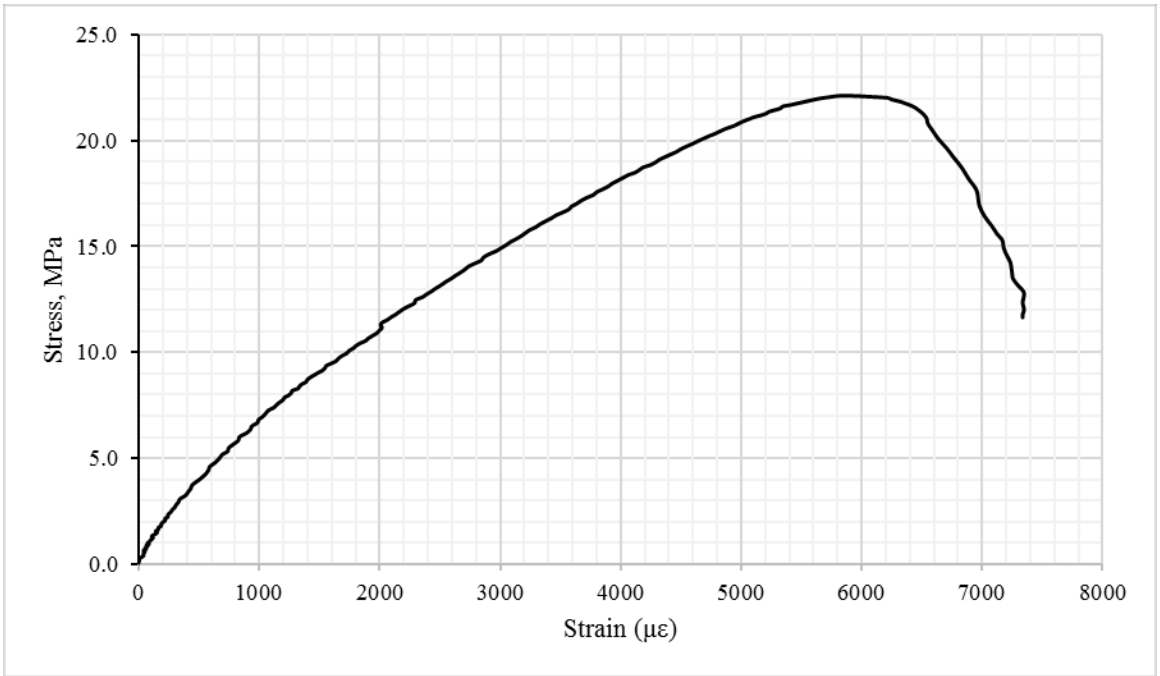

Figure 4-11: Stress - Strain Correlation for Mixture SM 2

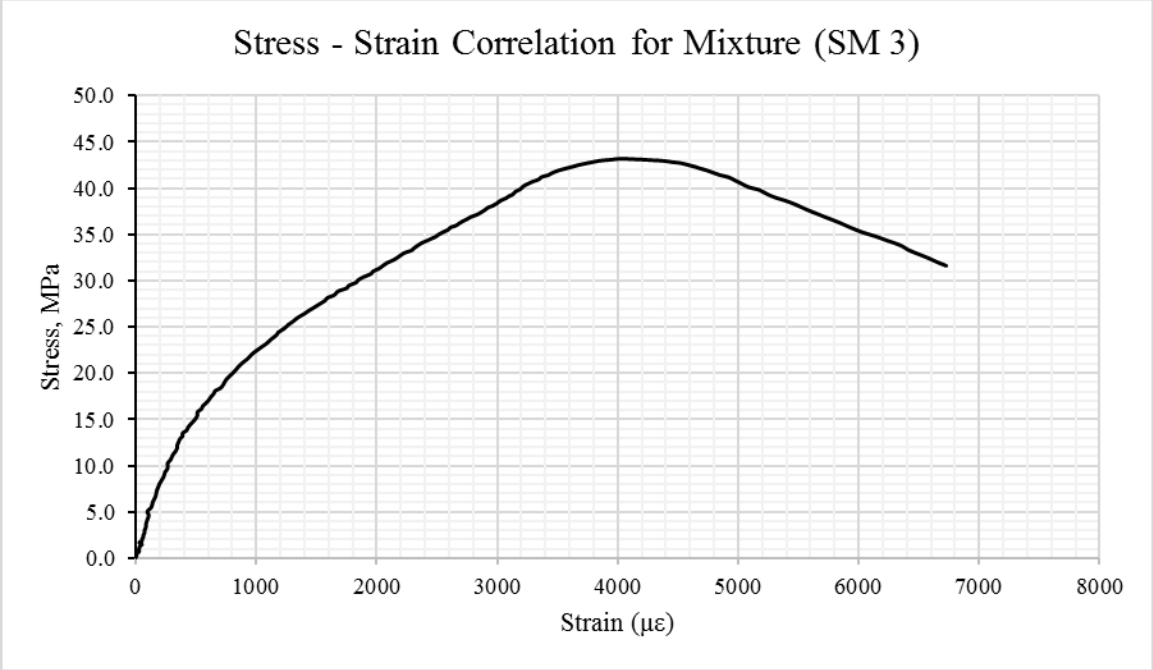

Figure 4-12: Stress - Strain Correlation for Mixture SM 3

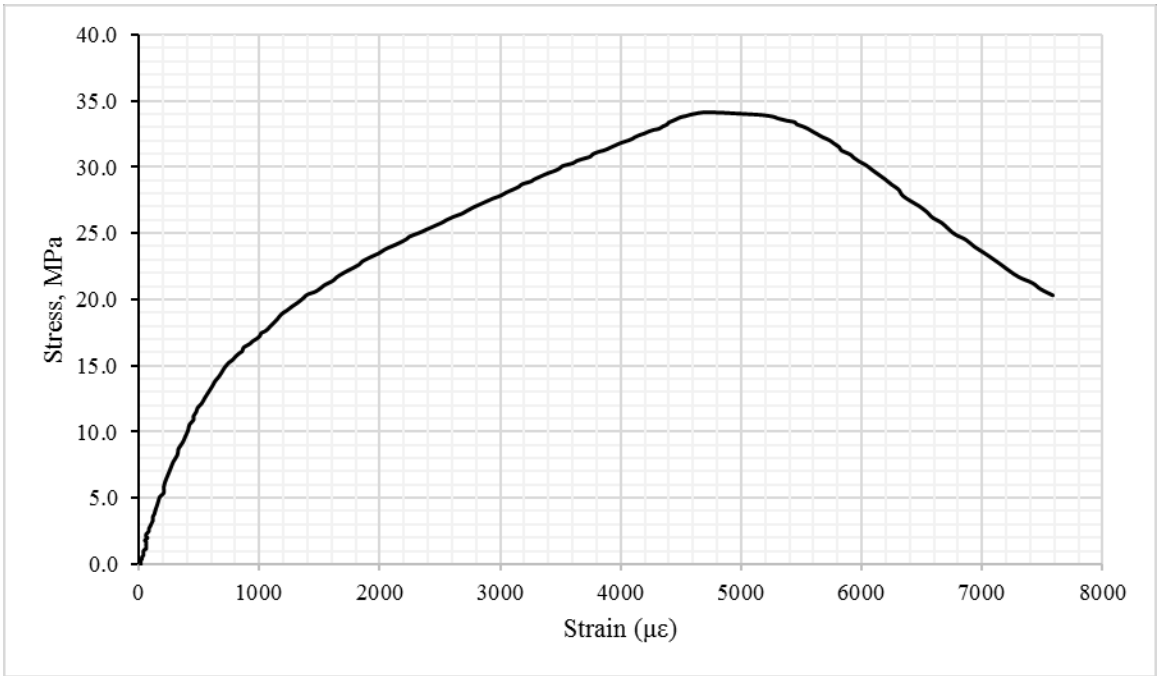

Figure 4-13: Stress - Strain Correlation for Mixture SM 4

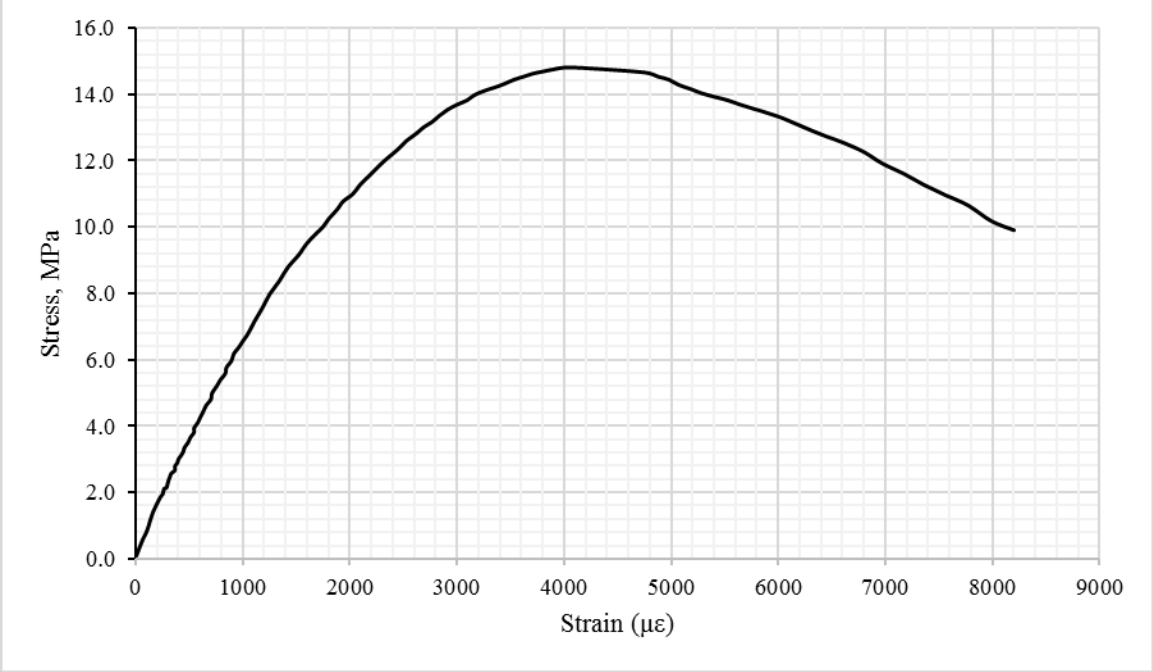

Figure 4-14: Stress - Strain Correlation for Mixture SM 5

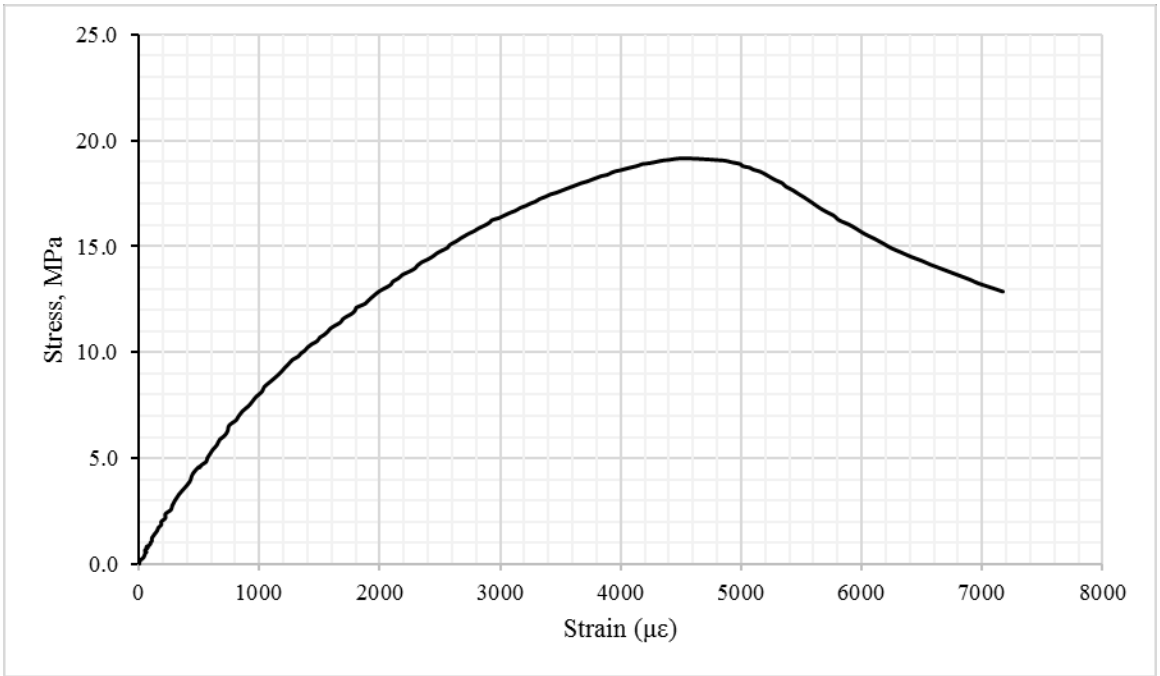

Figure 4-15: Stress - Strain Correlation for Mixture SM 6

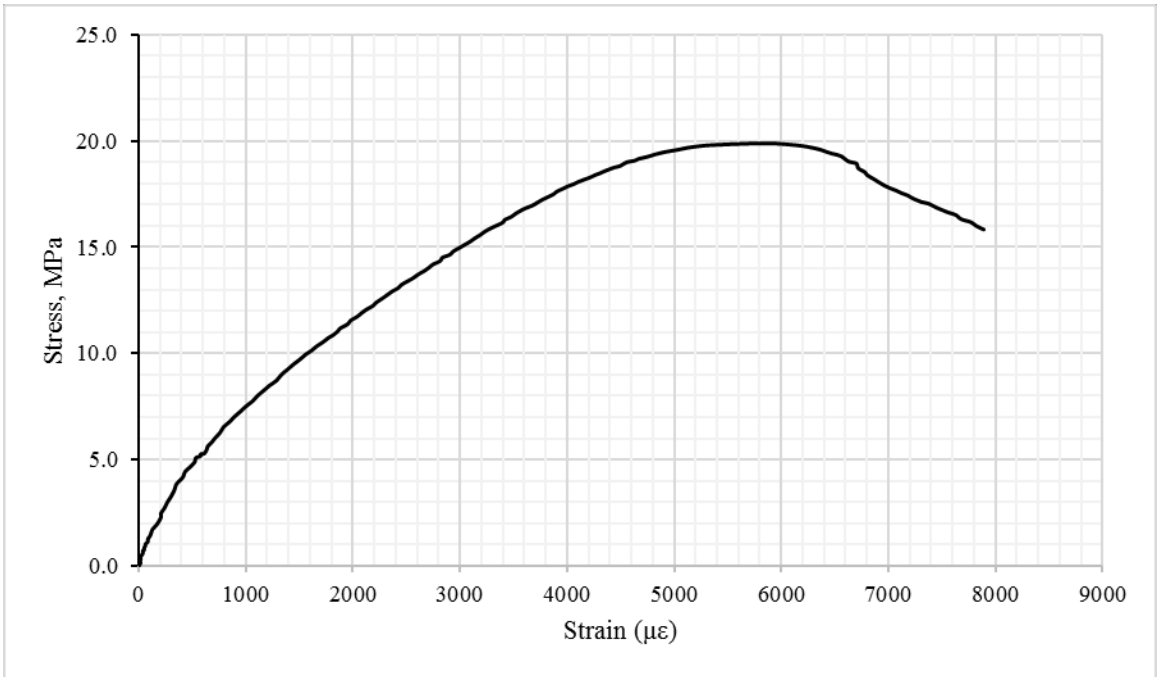

Figure 4-16: Stress - Strain Correlation for Mixture SM 7

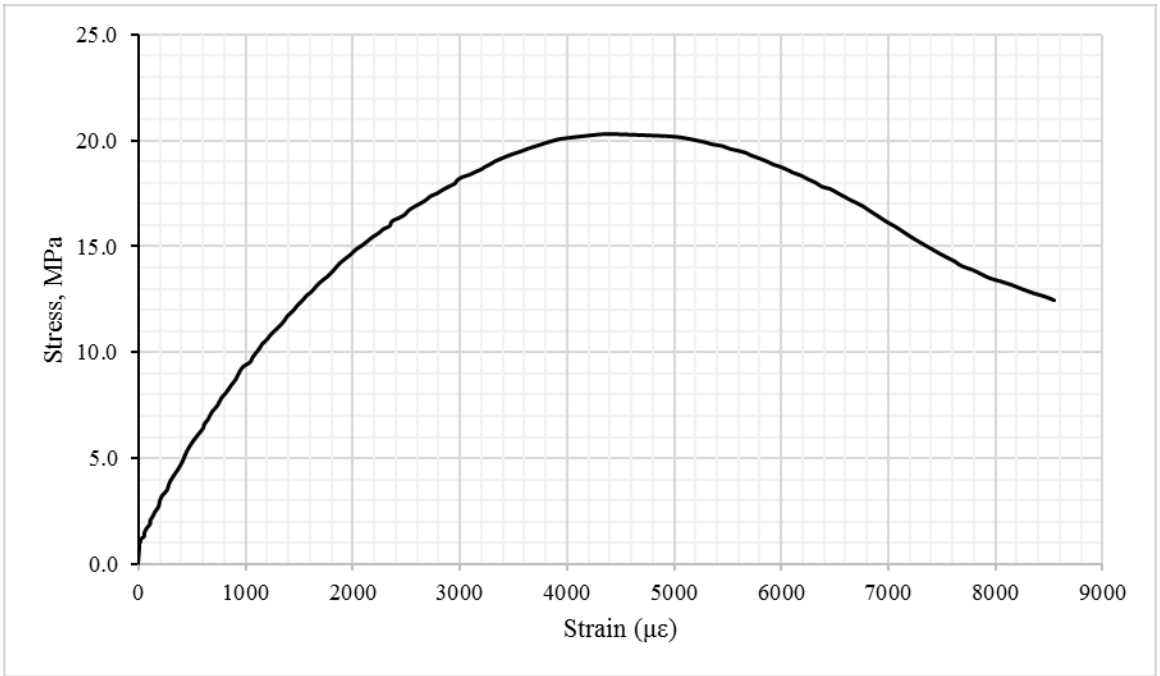

Figure 4-17: Stress - Strain Correlation for Mixture SM 8

The plots of modulus of elasticity of eight selected mixtures calculated using their respective stress-strain curves, as shown in Figures 4-10 through 4-17, are shown in Figure 4-18.

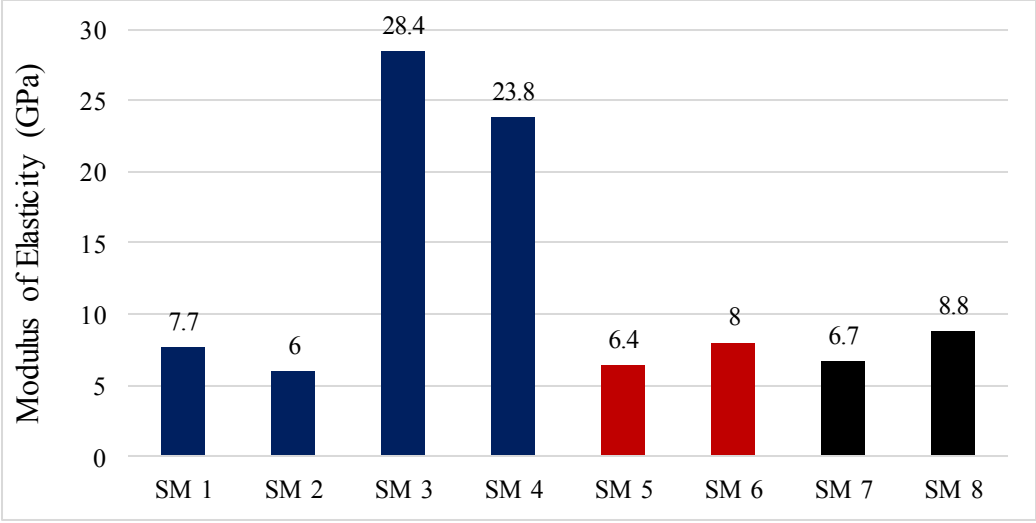

Figure 4-18: Elastic Moduli of Selected Geopolymer Concrete Mixtures

As can be seen from Figure 4-18, except mixtures SM3 and SM4 (NP-based mixtures with 85% NP and 15% Portland cement, treated by NaOH and KOH, respectively), all other mixtures have modulus of elasticity less than 14 GPa, which is a minimum value of elastic modulus for a normal strength Portland cement concrete. Therefore, for the applications where a high stiffness is required, the mixture SM3 or SM4 should be used.

Furthermore, it can be observed from Figure 4-19 that no good correlation exists between the compressive strength and modulus of elasticity of the selected geopolymer concrete mixtures.

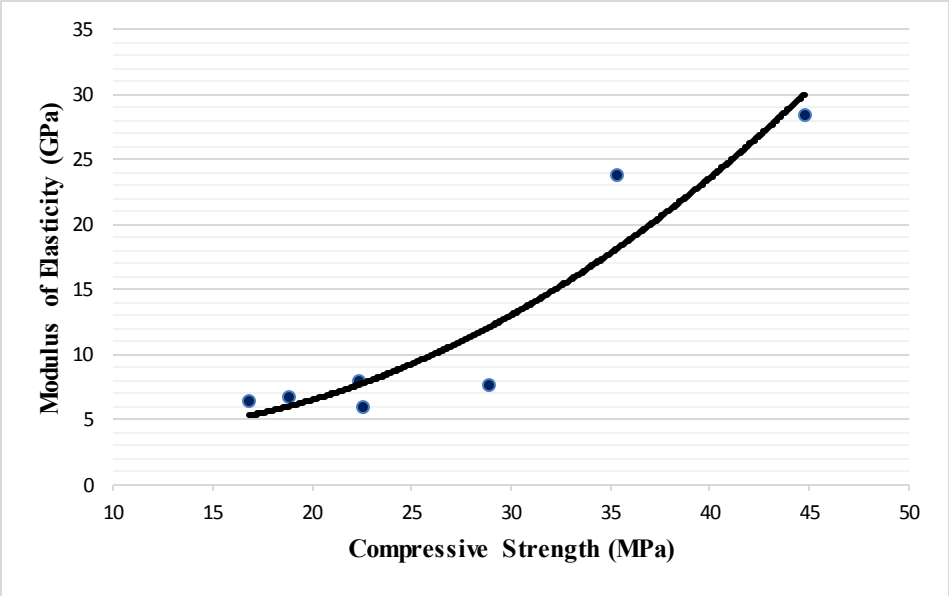

Figure 4-19: Correlation between Compressive Strength and Elastic Modulus of Geopolymer Concrete Mixtures

4.2.4 Water Absorption

The water absorption of the eight selected mixtures, obtained by testing specimens after 7 days of heat curing, are shown in Figure 4-20.

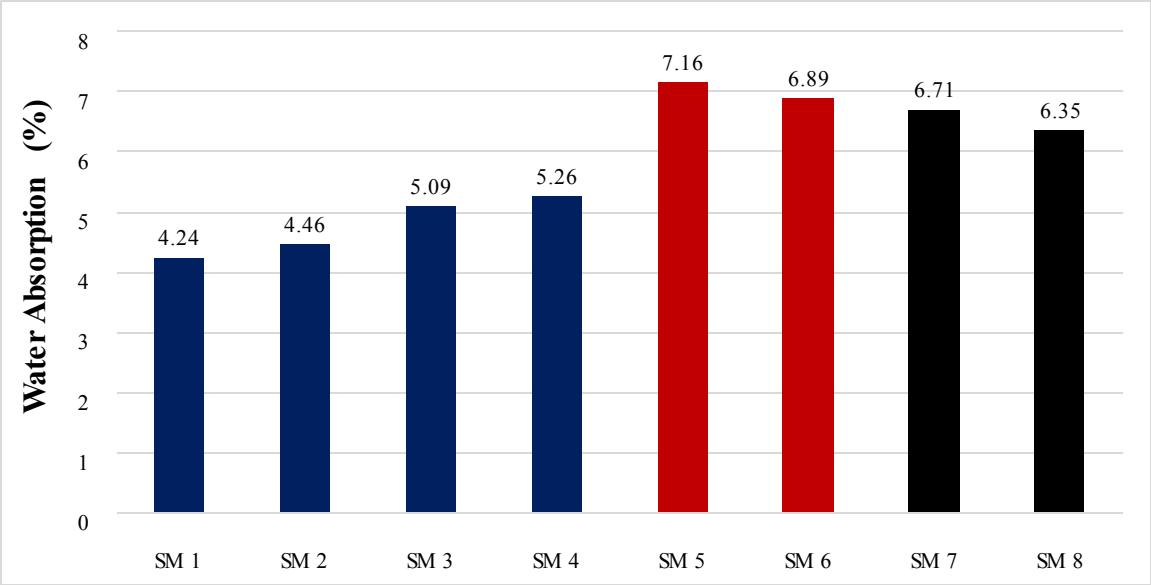

Figure 4-20: Water Absorption of the Selected Geopolymer Concrete Mixtures

As can be seen from Figure 4-20, NP-based mixtures have water absorption in the range of about 4 to 5%. The NP-based mixtures (SM1 and SM2) with 100% NP and no Portland cement had lower water absorption than the NP-based mixtures (SM3 and SM4) with 85% NP and 15% Portland cement. The kaolin and LSP-based mixtures had higher water absorption than other mixtures in the range of about 6 to 7%.

4.2.5 Acid Resistance

The percentage residual compressive strengths of the eight selected mixtures exposed to 3% hydrochloric acid for 28 days after 7 days of heat curing are shown in Figure 4-21. It can be observed from Figure 4-21 that the NP-based mixtures have much lower loss due to acid attack than that of the kaolin and LSP-based mixtures. Maximum of 47 % loss in compressive strength occurred in case of NP-based mixtures, whereas the kaolin and LSP-based mixtures lost up to 75% of their compressive strength due to the acid attack.

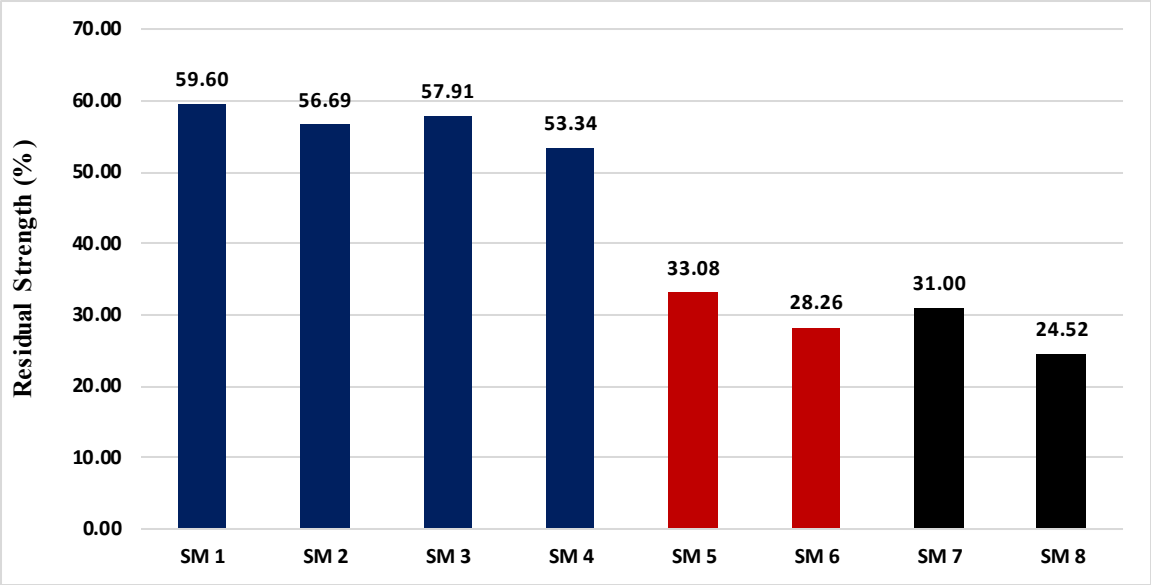

Figure 4-21: Residual Compressive Strength after 28 Days of HCl Immersion

4.2.6 Thermal Resistance

The percentage residual compressive strengths of the eight selected mixtures exposed to an elevated temperature of 300 ºC for 1 hour after 7 days of heat curing are shown in Figure 4-22.

It can be seen from Figure 4-22 that the NP and kaolin-based mixtures had a loss of compressive strength in a range of about 10 to 30 % whereas the loss of strength in case of LSP-based mixtures was about 50%.

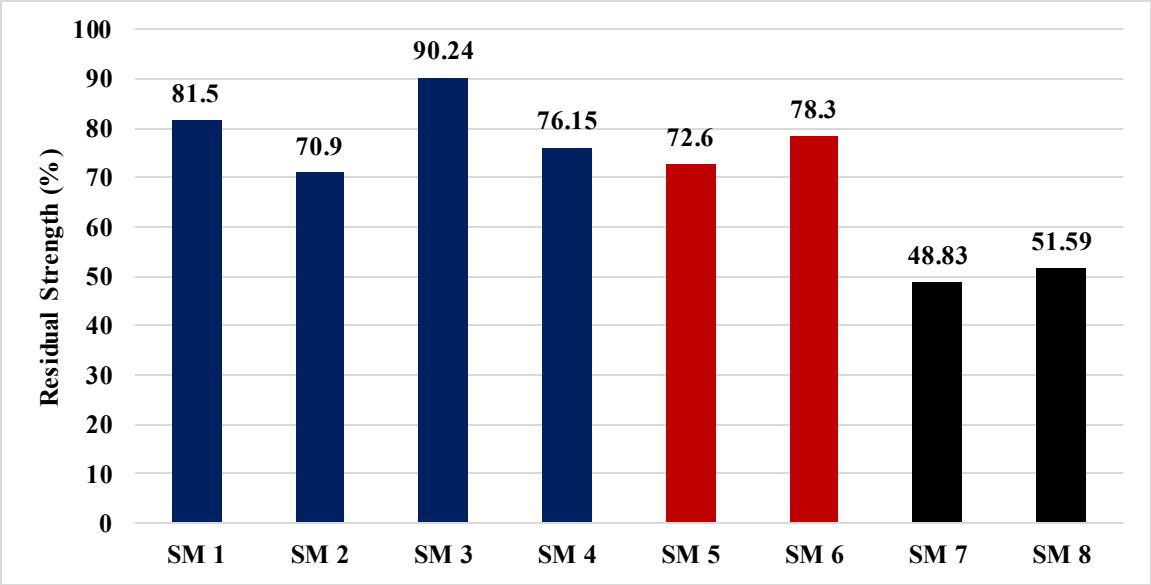

Figure 4-22: Residual Compressive Strength (%) after Burning @ 300°C for 1 Hour

4.2.7 Rapid Chloride Permeability

The current versus time curves of the eight selected mixtures, obtained by testing specimens for rapid chloride permeability after 7 days of heat curing, are shown in Figures 4-23 to 4-30.

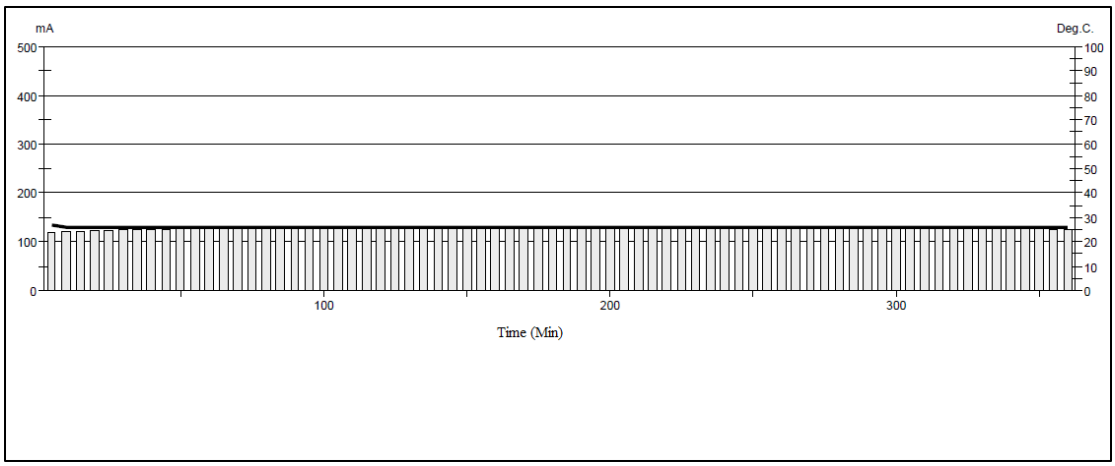

Figure 4-23: Current Versus Time Curve Obtained from RCP Test for Mixture SM 1

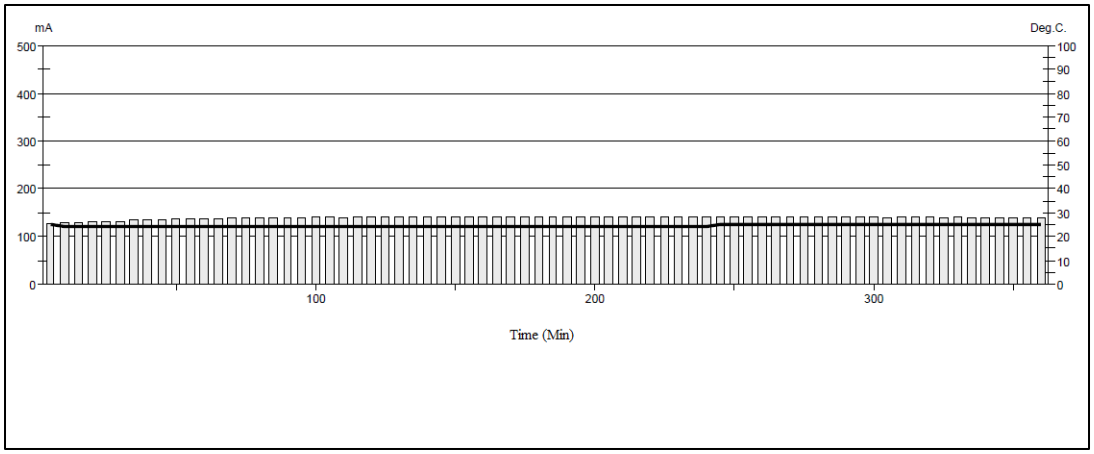

Figure 4-24: Current Versus Time Curve Obtained from RCP Test for Mixture SM2

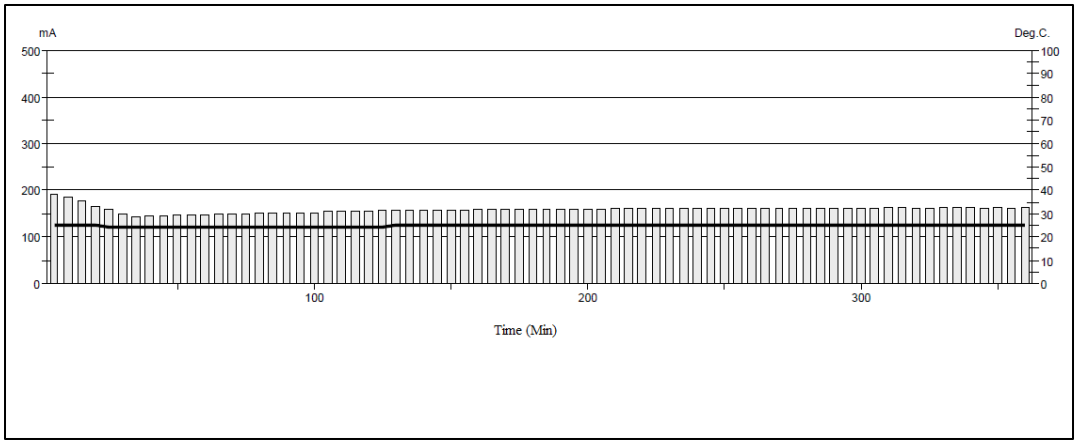

Figure 4-25: Current Versus Time Curve Obtained from RCP Test for Mixture SM3

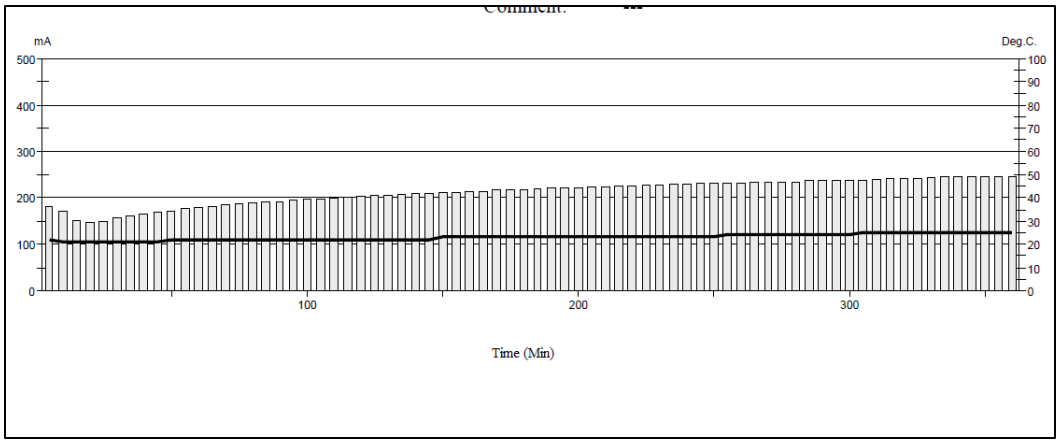

Figure 4-26: Current Versus Time Curve Obtained From RCP Test for Mixture SM4

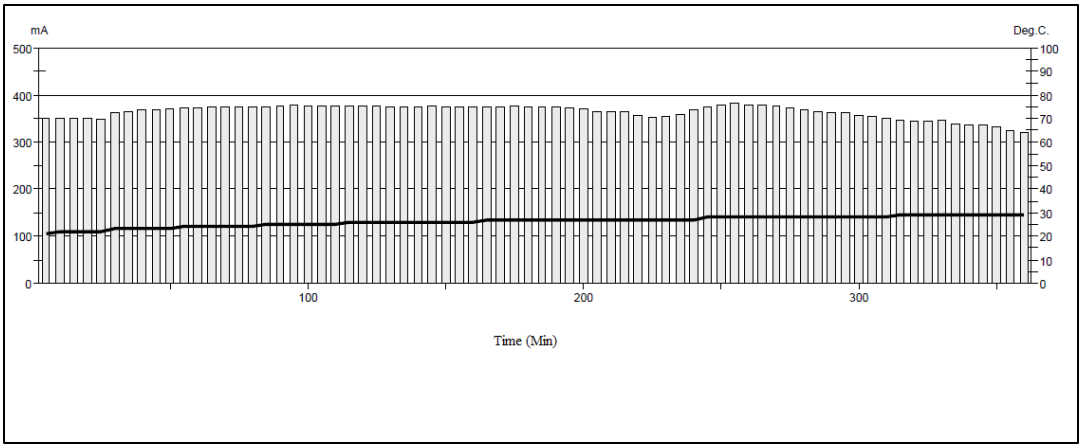

Figure 4-27: Current Versus Time Curve Obtained from RCP test for Mixture SM5

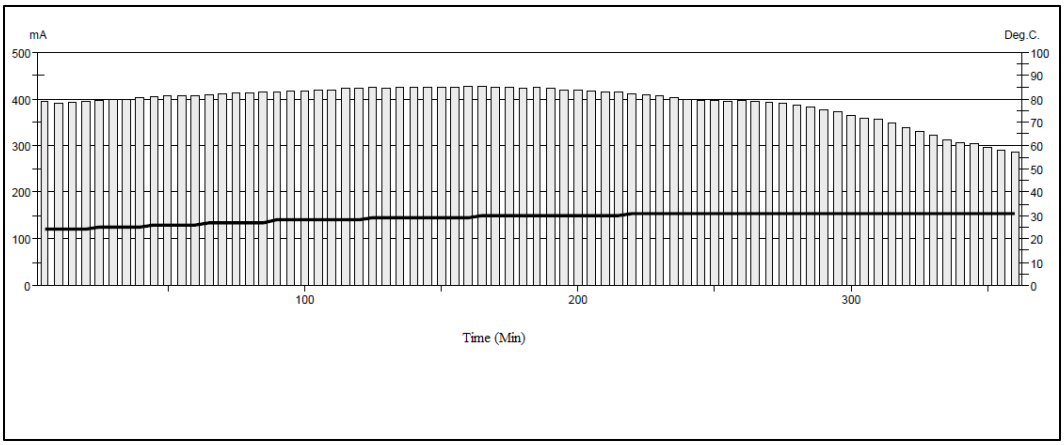

Figure 4-28: Current Versus Time Curve Obtained from RCP Test for Mixture SM6

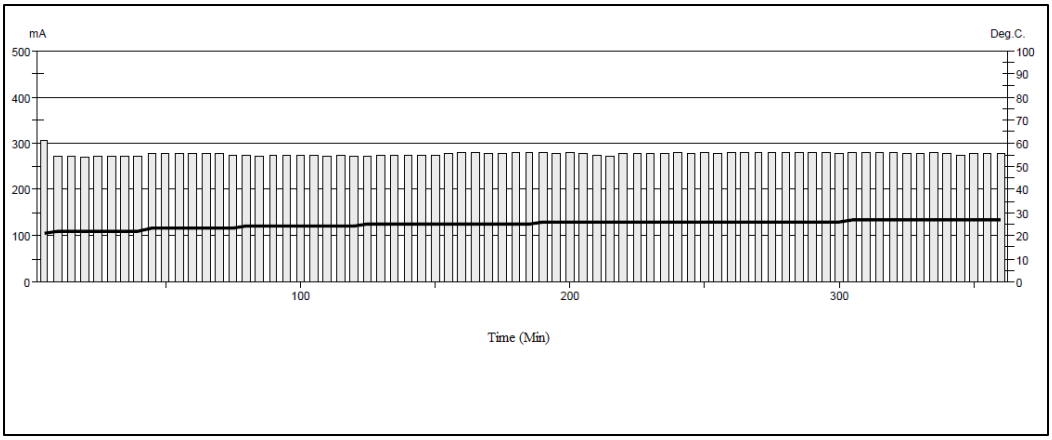

Figure 4-29: Current Versus Time Curve Obtained from RCP Test for Mixture SM7

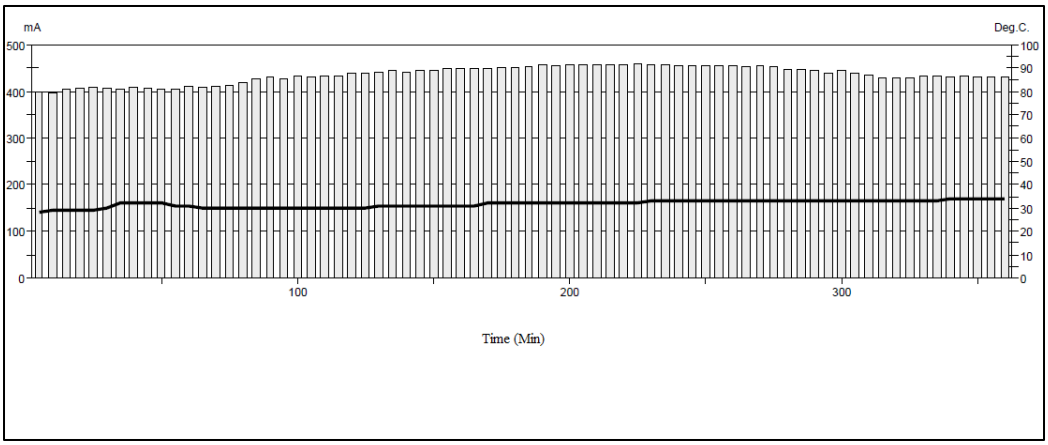

Figure 4-30: Current Versus Time Curve Obtained from RCP Test for Mixture SM 8

The plots of rapid chloride permeability of eight selected mixtures calculated using their respective current versus time curves, as shown in Figures 4-23 through 4-30, are shown in Figure 4-31.

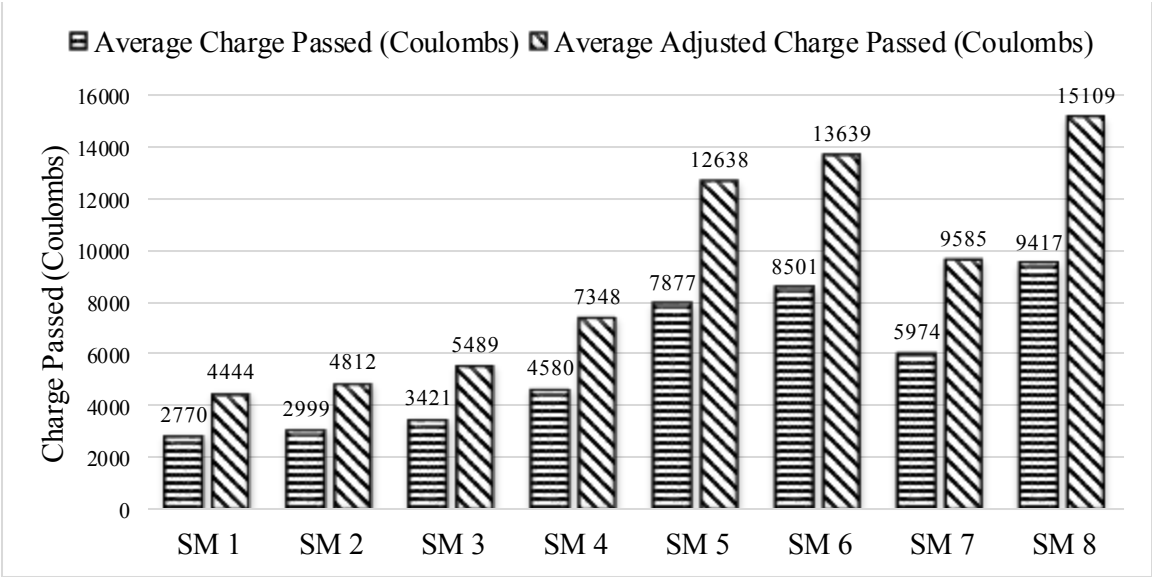

Figure 4-31: Rapid Chloride Permeability Test's Charge Passed (Coulombs)

It can be observed from Figure 4-31 that the NP-based mixtures have much lower rapid chloride permeability than that of the kaolin and LSP-based mixtures. However, the RCP test had been reported as ineffective to measure the chloride permeability for this type of concrete. The high alkalinity of the geopolymer concrete mixtures made RCP test not appropriate to indicate the chloride permeability class for this type of concrete [31].

4.2.8 Drying Shrinkage

The shrinkage versus time curves of the eight selected mixtures, obtained by testing specimens for drying shrinkage after 7 days of heat curing, are shown in Figures 4-32 through 4-39. All eight selected mixtures were heat-cured for 7 days before exposing them to air for monitoring the drying shrinkage. Therefore, the zero-time shown in the following plots (Figures 4-32 to 4-39) of drying shrinkage values correspond to the completion of 7 days of heat curing.

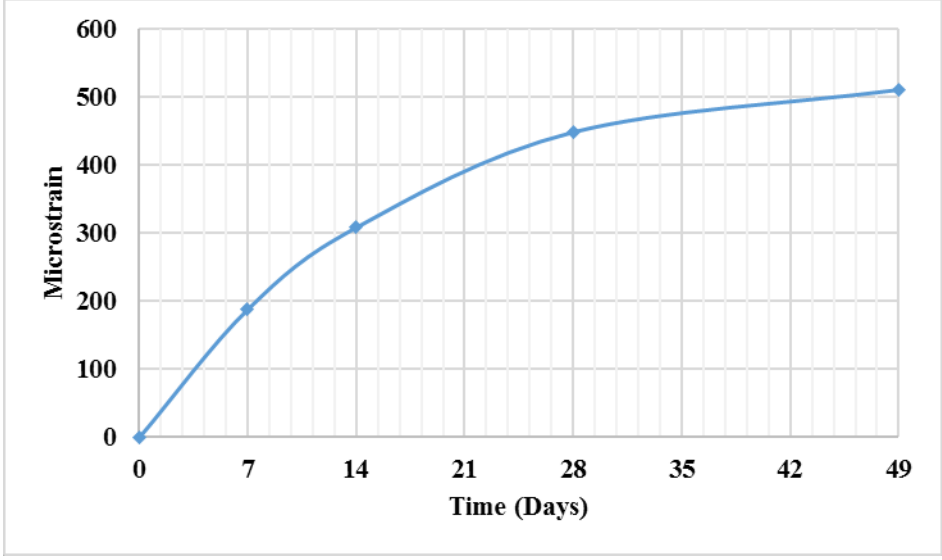

Figure 4-32: Variation of Drying Shrinkage with Time for Mixture SM1

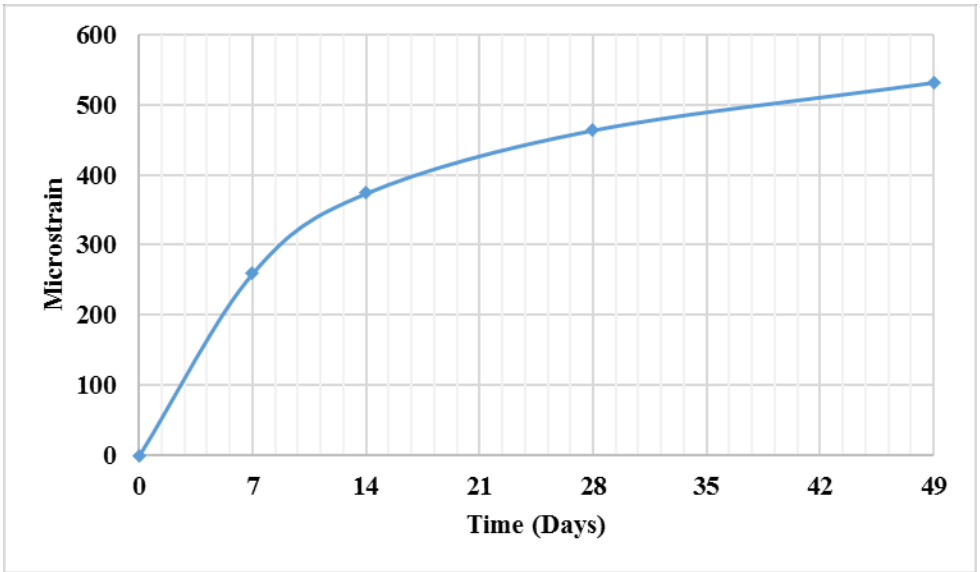

Figure 4-33: Variation of Drying Shrinkage with Time for Mixture SM2

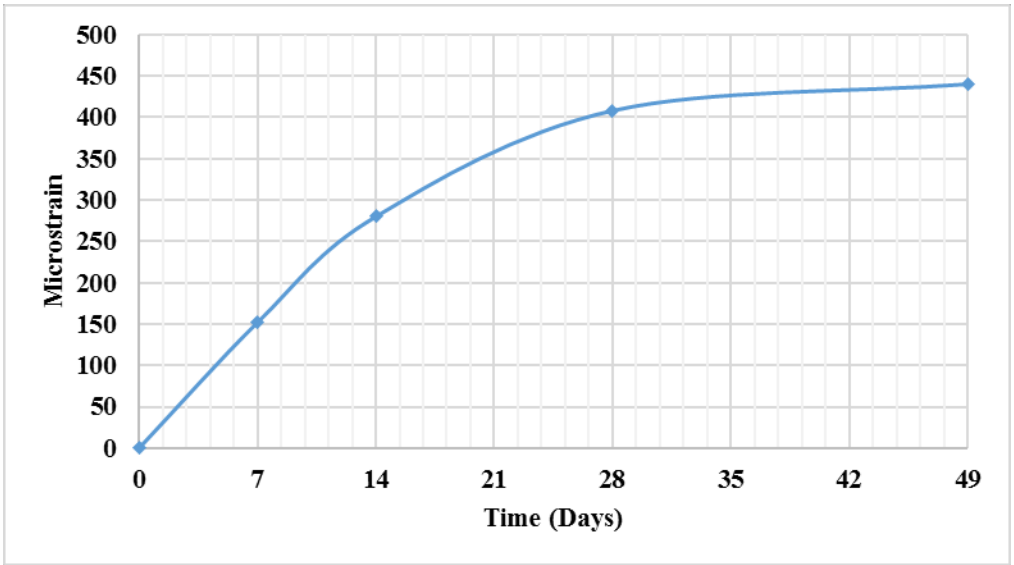

Figure 4-34: Variation of Drying Shrinkage with Time for Mixture SM3

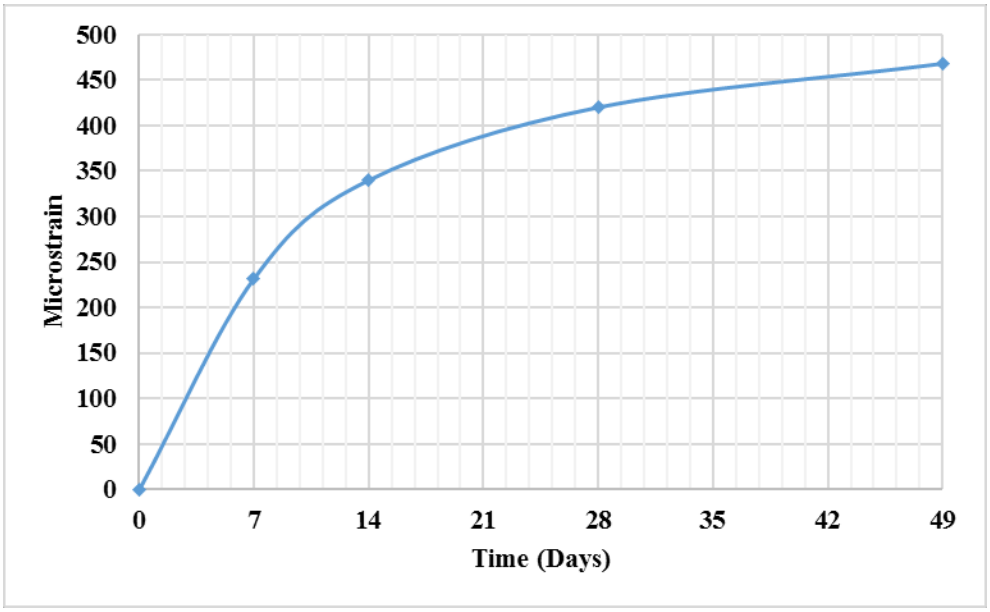

Figure 4-35: Variation of Drying Shrinkage with Time for Mixture SM4

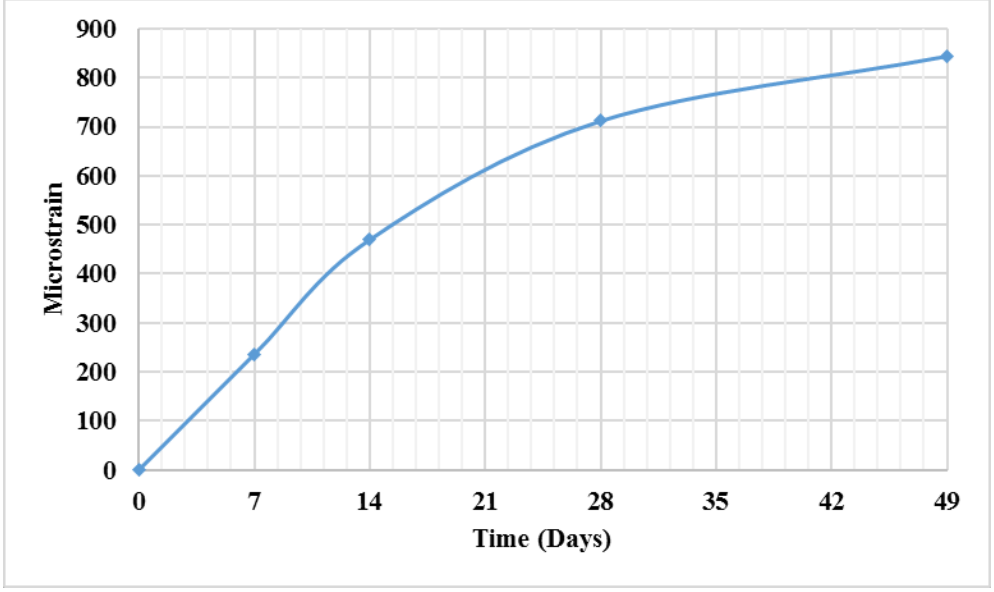

Figure 4-36: Variation of Drying Shrinkage with Time for Mixture SM5

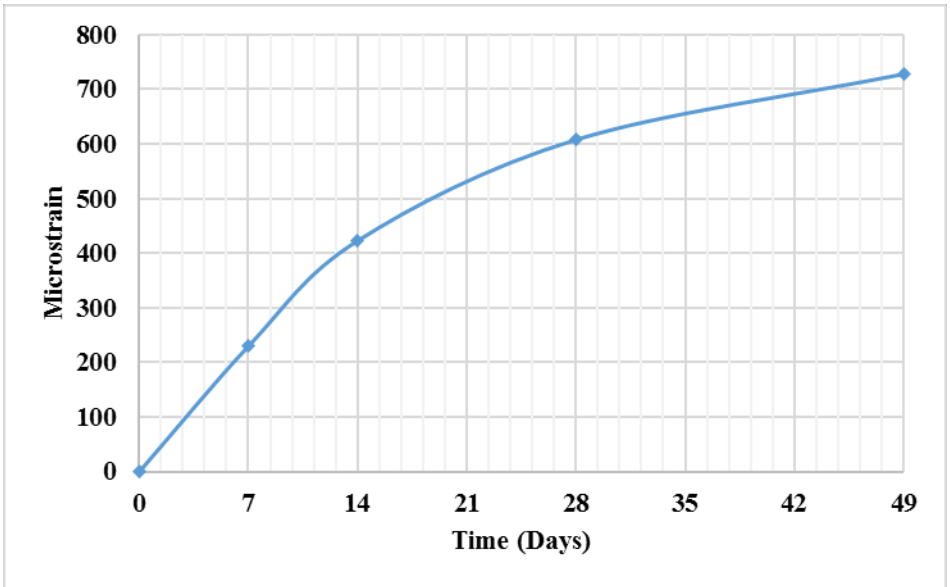

Figure 4-37: Variation of Drying Shrinkage with Time for Mixture SM 6

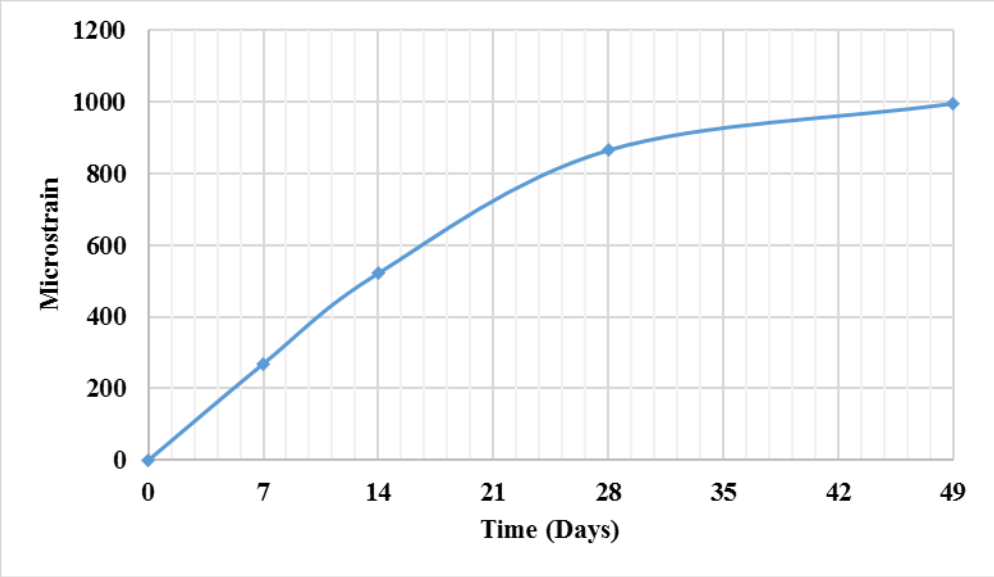

Figure 4-38: Variation of Drying Shrinkage with Time for Mixture SM 7

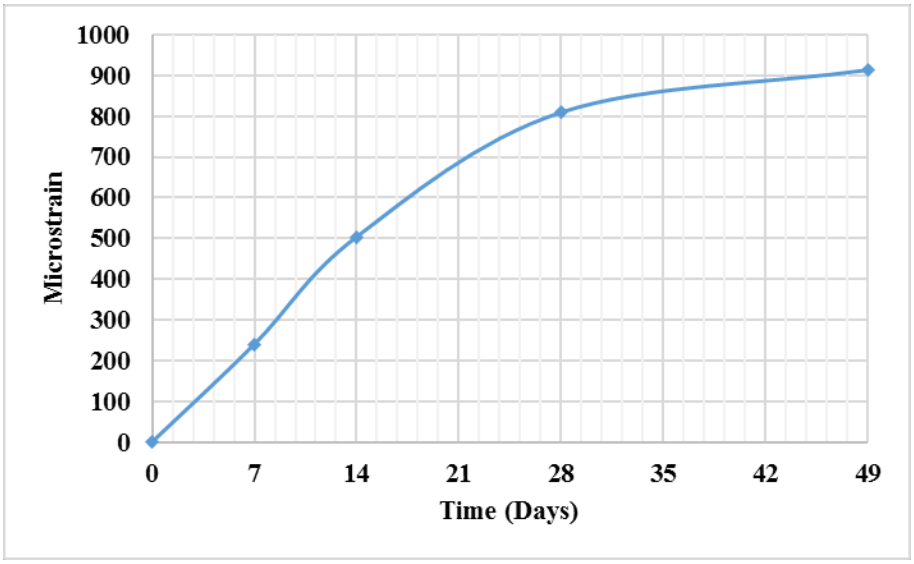

Figure 4-39: Variation of Drying Shrinkage with Time for Mixture SM 8

The measured drying shrinkage of the specimens of selected mixtures after 7 days of air exposure following their heat curing are shown in Figure 4-40. The 7-days shrinkage of the selected mixtures as plotted in Figure 4-40 are the values taken from the curves showing shrinkage variation with time (Figures 4-32 through 4-39).

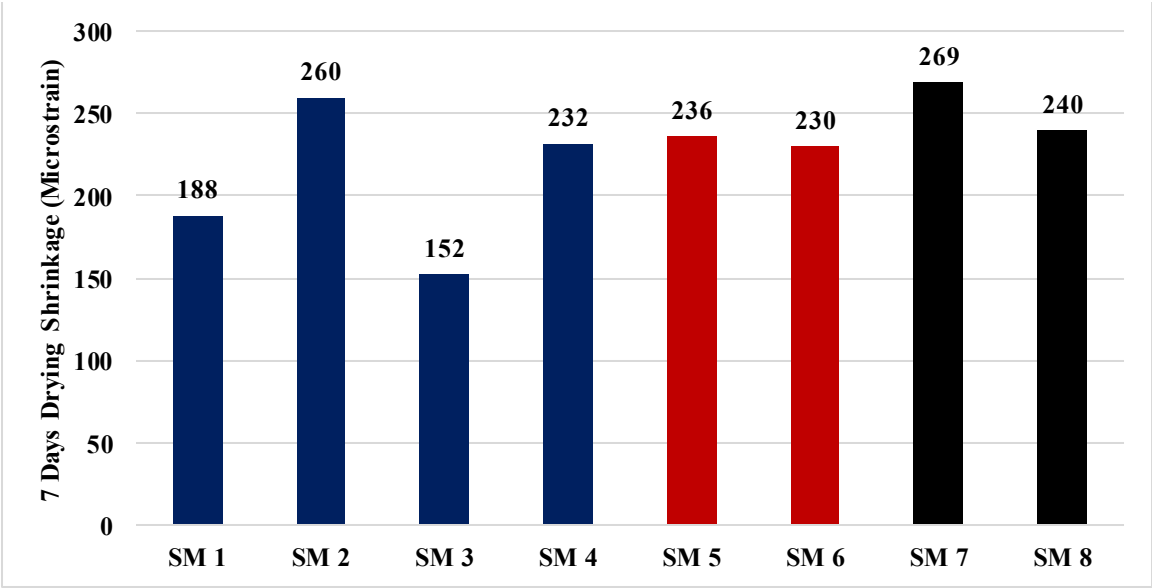

Figure 4-40: 7 Days Geopolymer Concrete Drying Shrinkage

It can be observed from Figure 4-40 that none of the eight mixtures showed 7 day drying shrinkage of more than 300 micro-strain. However, the shrinkage recorded after 7 weeks of air exposure is found to be in the range of 440 to 994 micro-strain. As can be seen from Figures 4-32 through 4-39, that after 7 weeks of air exposure the NP-based mixtures have shrinkage in the range of 440 to 532 micro-strain, kaolin-based mixtures in the range of 728 to 844 micro-strain, and LSP-based mixtures in the range of 914 to 994. From these observations, it can be concluded that the NP-based mixtures have highest resistance against drying shrinkage followed by kaolin and LSP-based mixtures, respectively.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

Based on the findings of this research, the following conclusions can be drawn:

1. Almost all 18 NP-based mixtures (nine treated by NaOH and other nine treated by KOH with Na_2SiO_3/NaOH and Na_2SiO_3/KOH ratios in the range of 1.0 to 4.0) had shown compressive strength above 20 MPa makingthem applicable as structural concrete mixtures.
2. One mixture from all 18 kaolin-based mixtures (nine treated by NaOH and other nine treated by KOH with Na_2SiO_3/NaOH and Na_2SiO_3/KOH ratios in the range of 1.0 to 4.0) had shown compressive strength above 20 MPa.
3. One mixture from all 18 limestone powder-based mixtures (nine treated by NaOH and other nine treated by KOH with Na_2SiO_3/NaOH and Na_2SiO_3/KOH ratios in the range of 1.0 to 4.0) had shown compressive strength above 20 MPa.
4. In NP-based mixtures, both NaOH and KOH are found to be effective in activation. However, in kaolin and limestone powder-based mixtures, KOH was more effective as an activator than NaOH.

5. The ANOVA conducted using the strength data, pertaining to each group of 54 trial mixtures of geopolymer concrete considered in this study, indicate that quantity of natural pozzolan, kaolin and limestone powder replacing Portland cement is more influential than the other factor which was Na_2SiO_3/NaOH or Na_2SiO_3/KOH ratios.
6. The equations obtained through linear regression of the strength data for each group of 54 trial mixtures indicate an excellent correlation between the compressive strength and the two key factors (Portland cement replacement level and alkali ratio) considered in the present work. These correlation equations can be used to optimize the Portland cement replacement level and alkali ratio for a given target strength.
7. The detailed evaluation of eight selected geopolymer concrete mixtures indicate that among the three materials considered, natural pozzolan is found the best performing. The use of kaolin and limestone powder for producing geopolymer concrete is not recommended because of their poor performance.
8. All the selected NP based mixtures showed splitting tensile strength above 2 MPa, which is a minimum value for normal structural concrete. However, the kaolin and LSP- based mixtures showed splitting tensile strength less than 2 MPa.
9. Except mixtures SM3 and SM4, NP-based mixtures with 85% NP and 15% Portland cement, treated by NaOH and KOH, respectively, all other mixtures had modulus of elasticity less than 14 GPa, which is a minimum value for normal Portland cement

concrete. Therefore, for the applications where a high stiffness is required, mixtures SM3 or SM4 should be used.

10. In NP-based mixtures, water absorption was found to be in the range of 4 to 5%. However, the kaolin and LSP- based mixtures showed higher water absorption than NP mixtures.
11. NP-based mixtures showed much lower loss in compressive strength due to HCl acid attack than that of the kaolin and LSP-based mixtures after 28 days of exposure. Maximum of 47 % loss in compressive strength occurred in case of NP-based mixtures, whereas the kaolin and LSP-based mixtures lost up to 75% of their compressive strength due to the HCl acid exposure.
12. NP and kaolin-based mixtures had lost around 10 to 30 % in compressive strength after burning at 300 ºC for one hour. Whereas, LSP-based mixtures lost around 50% in compressive strength after burning.
13. None of the selected eight mixtures showed 7 day drying shrinkage of more than 300 micro-strain. However, the shrinkage recorded after 7 weeks of air exposure was found to be in the range of 440 to 532 micro-strain for NP-based mixtures, 728 to 844 micro-strain for kaolin-based mixtures, and 914 to 994 for LSP-based mixtures, respectively.

5.2 Recommendations

The NP-based mixture SM3 (with 85% NP, 15% Portland cement) and activated using Na_2SiO_3/NaOH ratio of 4.0 and SM4 (with 85% NP, 15% Portland cement) and activated using Na_2SiO_3/KOH ratio of 4.0 are recommended for use as geopolymer structural concrete mixtures.

5.3 Recommendations for Further Studies

1. Possibility of using other waste materials, such as cement kiln dust, bag house dust, blast furnace slag, etc., should also be explored in producing geopolymer concrete.
2. The possibility of using silica fume along with other materials. Such as natural pozzolan, kaolin, limestone powder, fly ash, cement kiln dust, bag house dust, blast furnace slag, for improving the performance of the geopolymer mixtures should also be explored.
3. The possibility of developing geopolymer concrete cured at atmospheric temperature should be explored.

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